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THE OPERATIONAL FORECASTING/NOWCASTING OF PRECIPITATION TYPE IN THE SOUTHEASTERN UNITED STATES TYPE OF PRECIPITATION: DESCRIPTIVE AND OBJECTIVE GUIDANCE

by

CRAIG ALAN SOUZA

A thesis submitted to the Graduate Faculty of

North Carolina State University

in partial fulfillment of the

requirements for the Degree of

Master of Science

MARINE, EARTH, AND ATMOSPHERIC SCIENCES

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1994

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ABSTRACT

SOUZA, CRAIG ALAN. The Operational Forecasting/Nowcasting of Precipitation Type in the Southeastern United States Type of Precipitation: Descriptive and Objective Guidance. (Under the direction of Steven Businger)

Frozen and freezing precipitation are hazardous to modern society. Even small amounts of frozen or freezing precipitation can significantly affect the public in the southeastern United States (SEUS). Improved forecasts of and specificity of precipitation type are critical to public and private sector responses to wintry precipitation.

A significant percentage of frozen or freezing precipitation cases in this region are associated with shallow polar airmasses (i.e. Cold Air Damming {CAD} situations) and occur as a mix of wintry precipitation. CAD episodes are not routinely portrayed accurately by current operational numerical weather prediction models. Hence, right or wrong, there can be a lack of confidence in the model output statistics (MOS) generated from these models.

As a supplement to the MOS, a "Type of Precipitation: Descriptive and Objective Guidance" (TOP DOG) approach consisting of regression equations (conditional probability) and nomograms is developed regionally and for individual stations in the SEUS. Due to the frequency of mixed precipitation events in the SEUS, emphasis is directed towards specifying a variety of precipitation subtypes (e.g., mixed liquid but non-accumulating frozen, all snow vs. mixed accumulating frozen).. Six-hour precipitation type guidance is derived directly from climatological (1973-1991) upper air sounding and surface data. TOP DOG uses logistical regression, more representative of the phenomena than linear regression used previously.

The author provides a brief comparison with previous precipitation type forecast methods. The TOP DOG technique can be used with real-time upper air sounding data or in a perfect prog sense with gridded upper air analyses or model gridded data.

The TOP DOG approach investigates the use of thickness to forecast precipitation type. Tests of significance show that the thickness only approach is comparable to more complex (i.e. includes the use of other atmospheric variables such as temperature, humidity, etc.) and traditional approaches.

TOP DOG improves on traditional precipitation type forecast techniques. Subdivision of the traditional 1000-700 mb thickness layer into partial thicknesses (850-700, 1000-850mb) is not statistically significant for predicting frozen precipitation at individual inland stations in the SEUS. However, an additional subdivision of the 1000-850 mb thickness layer into partial thicknesses (1000-950/950-850 or 1000-900/900-850) is significant for predicting freezing precipitation. After inclusion of thickness, no variable other than the temperature at 950mb (freezing precipitation only) is significant.

Regionally, in the SEUS' Piedmont region, subdivision of the 1000-700mb thickness into partial thicknesses (850-700, 1000-850) is significant for predicting frozen/freezing precipitation. As expected, subdivision of the 1000-850 mb thickness layer into partial thicknesses (1000-950/950-850 or 1000-900/900-850) is significant for predicting freezing precipitation. After inclusion of thickness, only the temperature at 950mb (freezing) and the temperature 500mb (frozen) are significant.

Precipitation type forecasting in the SEUS requires use of variables that allow for quantification of CAD and the layer in which warm air overruns the cold air dome. This research shows that the 1000-950mb and 950-850mb

thicknesses provide the needed information. A case study is used to illustrate the operational use of this technique and to provide the reader insight into how TOP DOG accounts for CAD.

BIOGRAPHY

Craig Alan Souza was born during October 1965 in Framingham, Massachusetts. He is a resident of Plymouth, New Hampshire currently serving as a Captain in the United States Air Force. Craig is the oldest son of Alfred J. and Barbara L. Souza of Millis, Massachusets.

Craig graduated from Millis High School in 1983. He recieved his Bachelor of Science (Atmospheric Science with a Minor in Technical Mathematics) from Plymouth State College in 1987. A member of United States Air Force since May 1987, he attended Officer Training School (OTS) at Lackland Air Force Base, Texas. Craig was commissioned a 2nd Lieutenant, United State Air Force Reserve on 13 August 1987. He served as Officer-in-Charge of Detachment 4, 5th Weather Squadron's Cadre Weather Team and Assistant Staff Weather Officer to the 10th Mountain Division (Light Infantry), located at Fort Drum, New York, from August 1987 to July 1990. 1st Lieutenant Souza spent the months of May and June 1990 as the Staff Weather Officer to Joint Task Force 6. From July 1990 to July 1992, Craig served as the Officer-in-Charge of Operating Location F, 7th Weather Squadron and Staff Weather Officer to United States Army Europe's Southern European Task Force, headquarted in Vicenza, Italy. Captain Souza received a Master of Public Administration Degree from Troy State University in 1992. Captain Souza received a regular commission in the United States Air Force during February 1994.

Honors and awards include Craig's 1987 selection to *Who's Who Among University and College Students, Outstanding Young Men of America* in 1988, and *ΠAA* (National Honor Society for Public Affairs and Administration) in 1992. In 1990, lst Lieutenant Souza was selected Company Grade Officer of the First Quarter by both the 5th Weather Squadron and 5th Weather Wing. In April 1991, he was selected Company Grade Officer of the Quarter ending Mar 31, 1991 by the 7th Weather Squadron and 2nd Weather Wing. He has twice been awarded the Army Commendation Medal and is a receipient of the National Defense Service Medal. He has earned the Senior Meteorologist's badge. He has been selected to attend Squadron Officer's School upon completion of his course of study at NC State University.

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I am grateful to all my fellow USAF sponsored graduate students for their fellowship and support. Also, thanks to all my fellow graduate students who assisted me in the pursuit of scientific truth and knowledge.

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Last but definitely not least, I would like to thank the Lord for providing me with the talents and perseverance necessary to complete this difficult task.

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1 INTRODUCTION

1.1 Overview

Snow, freezing rain, and ice pellets (a.k.a. wintry precipitation[1]) dramatically affect society by disrupting lines of communication (e.g. roads, airports, microwave communications, etc.) and causing property damage (e.g. downed power lines, tree falls on property, etc.). Forecasting precipitation type in the Southeastern United States (SEUS), where wintry precipitation is relatively infrequent and typically occurs as a mix of wintry precipitation types, is particularly challenging . Here, even small amounts of wintry precipitation can significantly disrupt society and the public. Forecasting precipitation type is particularly difficult when forecasted temperatures are near freezing (Bluestein 1993; Keeter and Cline 1991).

Improved forecasts of and specificity of precipitation type are critical to public and private sector responses to wintry precipitation (snow removal/plowing, sanding/salting, road closures, etc.). Today, in this era of shrinking budgets and 'just in time' supply systems, more accurate, specific, and timely forecasts of precipitation type are critical to decision making processes and responses.

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[1] Rain/drizzle, Snow, Ice Pellets, and Freezing Rain/drizzle are the four major types of wintry precipitation. (Glossary of Meteorology, 1959). Understanding their definitions is critical to this research. Snow is white or translucent ice crystals of a complex branched hexagonal form that is often agglomerated into snowflakes. Ice pellets are transparent or translucent spherically, irregularly, or conically shaped pellets of ice, 5mm or less in diameter. These pellets bounce on hard ground and make a sound on impact. Ice Pellets, type I (a.k.a. Sleet) are transparent and are formed primarily by the freezing of raindrops or refreezing of largely melted snowflakes. Type II ice pellets (a.k.a. Small Hail) are translucent and are snow pellets covered in a thin layer of ice. Freezing rain or freezing drizzle falls in liquid form (usually supercooled) but freezes upon impact with surface based objects to form a coating of glaze (a.k.a. Clear Icing above the surface).

Particularly in the Southeastern United States where wintry precipitation occurs during a transition amongst various precipitation types, forecasters are challenged to provide increased forecast specificity of mixed precipitation types.

Precipitation type forecast products and procedures have been developed by the Technical Developments Laboratory of the National Weather Service (Erickson 1994, Erickson et al, 1993; Dallavlle et al, 1992; Bocchieri and Maglaras 1982; and Bocchieri 1979). Recent efforts by Heppner 1992 and Keeter and Cline 1991 to develop a forecaster-friendly precipitation type forecast for the northeast United States and North Carolina respectively, have met with some success. Forecast techniques available to the operational forecaster should be sophisticated enough to account for a thorough understanding of forecasting precipitation type but simple enough to be used in a timely and consistent manner. Current operational precipitation type forecasting techniques, including the NGM MOS and local procedures such as Keeter and Cline's Local Objective Guidance/Precipitation Type (LOG/PT) are incomplete due to their lack of specificity of mixed precipitation subtypes and their inclusion of ice pellets in their freezing rain forecasts. As a supplement to NGM MOS and local forecast procedures, the Type of Precipitation: Descriptive and Objective Guidance (TOP DOG) was developed.

1.2 Forecasting Wintry Precipitation Type

1.2.1 Synoptic Overview, Atmospheric Thermal Structure and Geographical/Topographical Influences

Understanding and accounting for the influence of the geography and topography of the Southeastern United States (SEUS) is critical to an accurate forecast. The SEUS is surrounded by the Appalachian mountains to the west and the Atlantic Ocean and the accompanying warm Gulf Stream to the east. The region also provides a favorable location for cyclogenesis and cold air damming which contributes to forecast and the majority of wintry occurs during periods of cold air damming. (Keeter et al. 1993; Bluestein 1993; Lee, et al. 1992; Bell and Bosart 1988; and Richwein 1980). Figure 1.1 shows a schematic of the most common flow field that is associated with cold air damming. Typically, a cold high pressure system is located over the northeast United States bringing a cold dry polar air flow southward along the east slopes of the Appalachian Mountains. Cold air damming can be recognized by a 'U' pattern in the surface pressure field (Bell and Bosart, 1988). Offshore, air flow from the southeast through east is modified as it crosses the gulf stream. A coastal front or more often a Piedmont front develops and the warm moist air overruns the cold air dammed along the eastern slopes of the Appalachians (Businger et al. 1992a; and Lee et al. 1992).

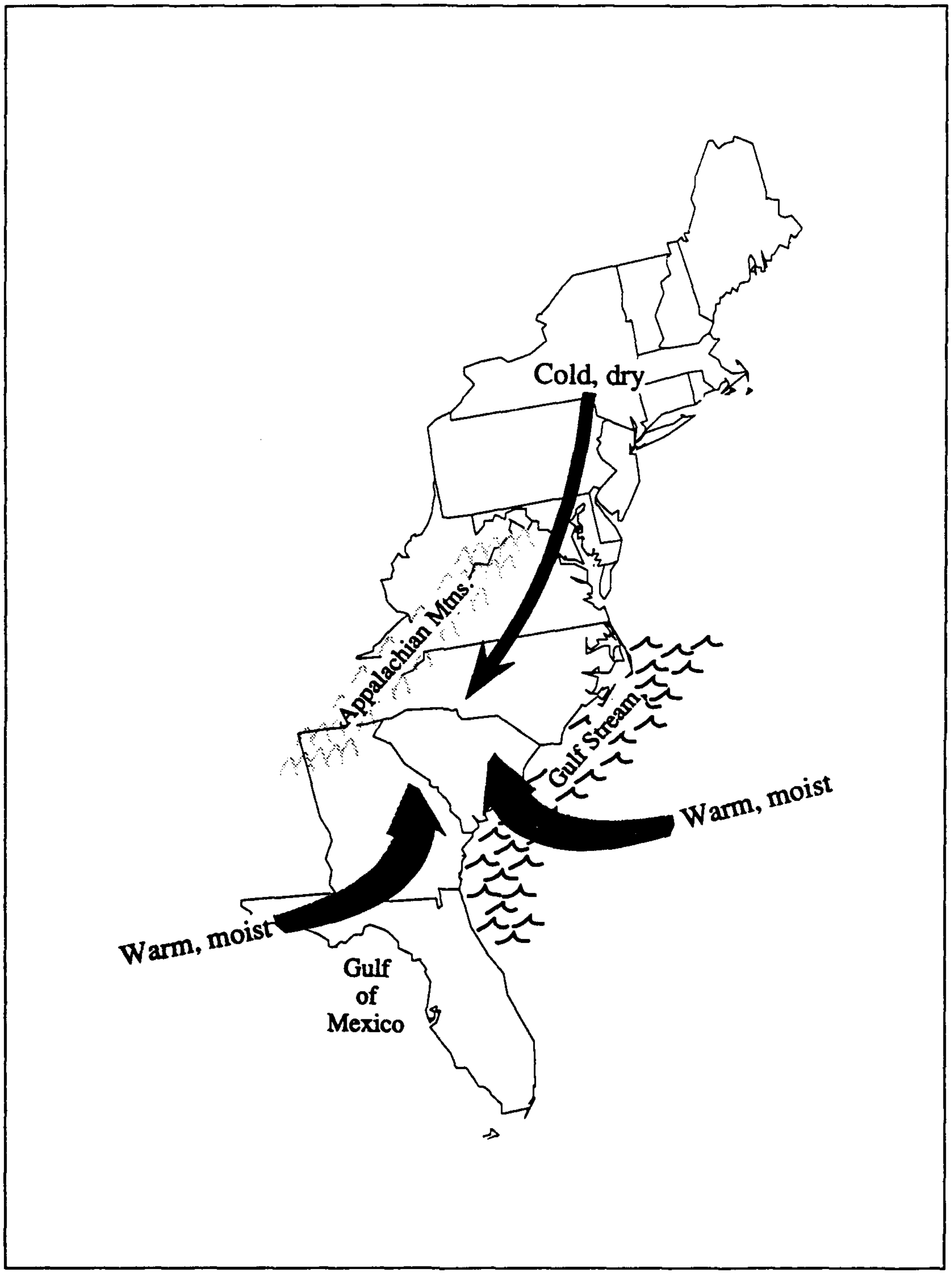

Figure 1.1, Schematic Flow Field Producing Wintry Precipitation in the Southeastern United States.

Additionally, a Southerly flow from the Gulf of Mexico associated with the synoptic scale warm front and the warm sector of the approaching surface cyclone overruns the cold air. This conveyor belt system is similar to the one described by Stewart (1992) for east coast storms in the Canadian Maritimes.

Wintry (frozen and freezing) precipitation is typically located ahead of (i.e. on the cold side) and to the north of the warm front and west of the Piedmont/coastal front. The width of the transition zone from rain (liquid) precipitation to freezing rain and/or ice pellets to snow is related to the relative strength of low to mid-level thermal advection patterns, and other adiabatic and diabatic processes including rising motion, evaporative cooling, and melting/refreezing, etc. Typically thermal advection dominates all other processes once precipitation is falling. (Stewart and King 1987; Stewart 1987) Keeter, et al (1993) categorizes two types of precipitation type transition zones. Just prior to the onset of precipitation, if the airmass in place over the SEUS is cold and dry enough (temperatures within 5°C of freezing and dewpoints below freezing), and thermal advection in the low and mid layers are weak, a broad area of mixed precipitation will likely develop due to the diabatic effects of evaporative cooling. A broad transition zone is common with weak or disorganized areas of low pressure along the east coast where warm moist air overruns the cold, dry air associated with cold air damming. (See Fig. 1.2b). Alternatively, a narrow transition zone of mixed precipitation is associated with well-organized low pressure systems where

the low level thermal advection patterns are relatively strong and well-organized. (See figure 1.2a).

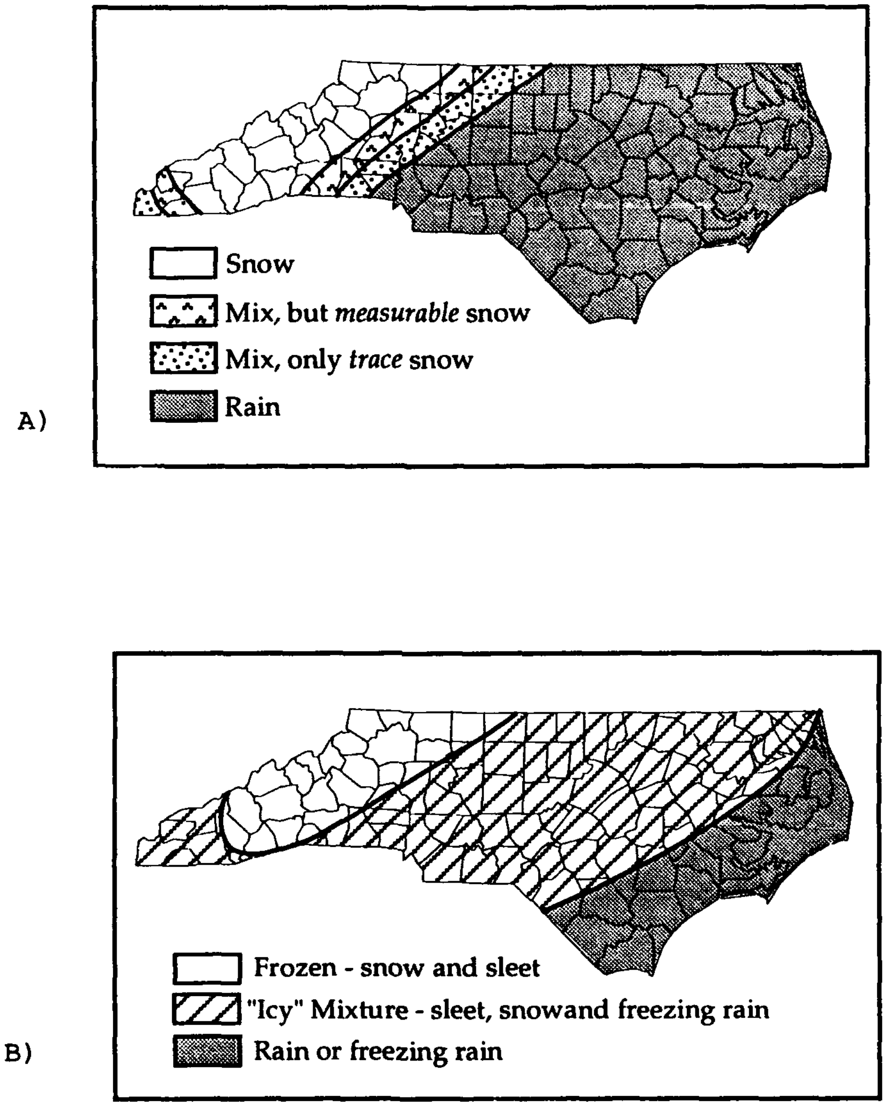

Figure 1.2. A) Traditional Precipitation Type Pattern (Narrow Transition Zone). B) Broad Precipitation Type Transition Zone Associated with Weak or Disorganized Surface Pressure Systems (Keeter, et al. 1993).

Precipitation type is dependent on the thermal structure of the lower atmosphere (i.e. the lower troposphere). Figure 1.3 illustrates the thermal structures associated with the three most hazardous types of wintry precipitation. Temperatures below 0^oC (below freezing) from the level of precipitation formation to the surface result in snow. A significant layer above the surface with temperatures above 0^oC will allow for the falling snow to melt prior to reaching the surface. Freezing precipitation may originate as a rain or as snow that melts when it falls through this region. Rain and freezing rain typically fall through a layer of relatively shallow cold air (temperatures at or near freezing). In freezing rain situations, the droplets supercool and then freeze upon impact with surface objects whose temperatures are below freezing. If surface temperatures are above freezing, precipitation falls as rain. If the surface based cold air is sufficiently deep, the liquid precipitation passes through a below freezing region of sufficient depth to allow for it to refreeze either into snow or ice pellets. Evaporative cooling plays a key role in initially dry atmospheres and often cools sufficiently to allow for the low to mid-levels to drop below the freezing mark. (Penn 1957; Stewart 1987; McNulty 1988; Businger et al 1992b; and Stewart 1992). Soil temperature also plays a role in accumulation of frozen precipitation (see Brown 1988 for a discussion).

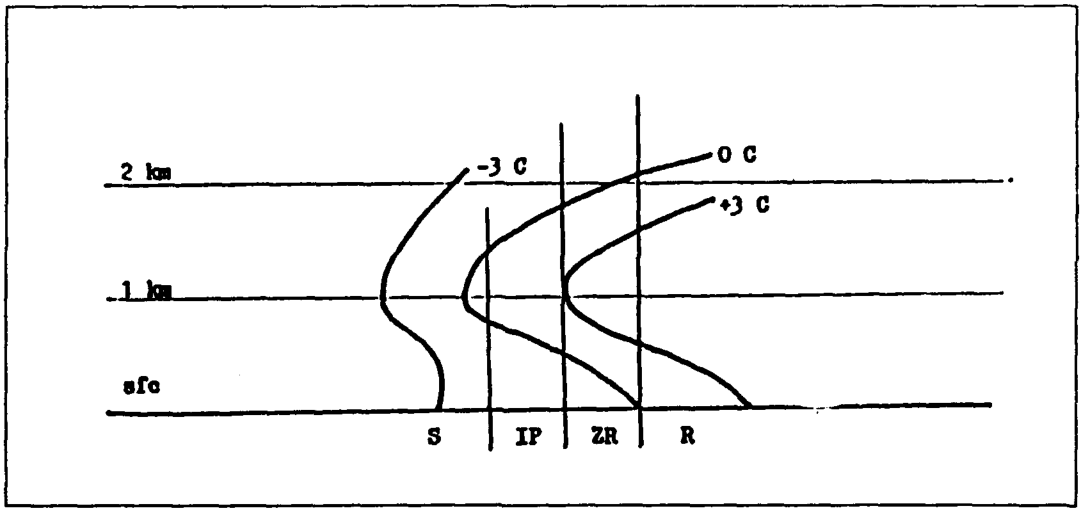

Figure 1.3. Schematic of Thermal Structure for Snow(S), Ice Pellets (IP), Freezing Rain (ZR), and Rain (R). (McNulty, 1988).

1.2.2 Current and Historical Forecast Methods

Erickson , 1994 notes that the Nested Grid Model's Model Output Statistics (NGM MOS) is deficient when forecasting precipitation type in areas of very shallow cold air such as those common in the southeastern United States during cold air damming situations. Note that a significant percentage of frozen or freezing precipitation cases in this region are associated with these shallow polar airmasses. Additionally, the NGM often does not retain the low-level cold air long enough so that if a cold air damming situation is present, the NGM MOS guidance may need to be modified. It is therefore incumbent upon the forecaster to consider the overall precipitation type pattern within fully developed or developing winter storms (Keeter et al, 1993; Stewart, 1992; and Carey, 1988) rather than a 'model parrot' approach that strictly relies upon objective precipitation type guidance from

the numerical weather prediction models or local/regional forecast schemes. (Brody, 1988).

Although not simple, the prediction of rain versus snow is often easier than the forecast of freezing precipitation or ice pellets. Traditionally, operational forecasters have used critical thickness values for forecasting precipitation-type. Thickness values provide the forecaster with a relatively crude indicator of the thermal structure of the lower atmosphere (Bluestein, 1993; Brenton, 1973; and Penn, 1957). Historically, the 1000-500mb thickness (Penn, 1957; and Lamb, 1955) was the key value provided to the forecaster over the National Digital Facsimile (DIFAX) and other facsimile networks used by the precipitation type forecaster. A critical 1000-500mb thickness of 5400m (a.k.a. the 540 line) provided the 50% probability demarcation line of snow versus rain. Modifications to this 'magic number', such as 5340 m for snow along the east coast and 5520m in the Rocky Mountain region were common. (Bluestein, 1993; and Heppner, 1992). Unfortunately, the 5400m thickness approach often is unreliable due to the rapidly changing thermal structure of the low to mid-levels of the atmosphere. The critical thickness approach is much more reliable during cold-air damming events where thermal advection patterns at the low- and mid-levels are more stable and organized.

Due to the relatively shallow nature of cold-air damming, the 1000-500mb thickness is normally too blunt an instrument to forecast precipitation type. Subdivision of the 1000-500mb thickness into shallower layers (e.g. 1000-700, 1000-850, 850-700, etc.) have been used operationally. Hanks, et al. (1967)

indicated that a 1000-700mb thickness of 2840m accurately delineated the border between rain and snow. Koolwine (1975) found a critical 1000-850mb thickness of 1314m for rain versus snow (Ontario, Canada). Most recently, Keeter and Cline (1991) indicate a critical 1000-700mb thickness of 2845m for liquid versus measurable frozen precipitation (SEUS: NC). They further suggest critical ranges for 1000-850mb thickness of 1280-1290 and 850-700mb thickness of 1540-1560m for frozen versus liquid precipitation. Heppner (1992) indicates critical thickness ranges of 1285-1300m for 1000-850mb, 1520-1540m for 850-700mb, and 2810-2830 for 1000-700mb (PA/NY). Snow may still occur with relatively high thickness values, often associated with deep near-freezing isothermal layers, if the lower levels are significantly cold and/or contain a cold layer of significant depth. (Bluestein, 1993; Stewart, 1992).

Critical thickness values or ranges are just one approach to the precipitation type forecast problem. Other approaches rely on melting layers or other forecast parameters to supplement the critical thickness approach. McNulty (1988) summarized that melting layers of 230-460 m provided sufficient melting regions for a change from snow to rain.

Forecasting freezing precipitation is one of the most difficult tasks faced by the operational forecaster today. Differentiating freezing precipitation from ice pellets in a forecast is even more difficult. The NGM MOS includes ice pellets in its freezing precipitation type category. (Erickson, 1994; Dallavalle, et al 1992; and Bocchieri and Maglaras, 1983). Keeter and Cline (1991) included accumulations of

ice pellets in their frozen type category (similar to the old Limited Fine Mesh Model's (LFM) MOS). Today's complex transportation system requires additional specificity not available in the NGM MOS. For example, various sectors of the public and government react differently to a forecast of freezing rain versus ice pellets or snow.

Melting layers of 0-200 m are typically associated with all snow. Transitional precipitation (mixed rain/snow, ice pellets, etc.) is often associated with melting layers of 200-400 m while all rain is expected when melting layers exceed 400m. Cantin and Bachand (1990) tie together both synoptic pattern recognition and partial thickness as tools to forecast precipitation type. Stewart (1992) uses the nomogram approach to illustrate the relationship between surface temperature, relative humidity, and precipitation type. His research illustrates the importance of evaporative cooling in precipitation type forecasting.

McNulty (1988) notes that freezing rain and ice pellets both form when snow falls through a warm layer and melts partially or completely. Freezing rain and ice pellet cases can occur when the snow completely melts prior to entering the freezing layer near to the surface. The author found that if temperatures in the subfreezing layer are warmer than -10°C, freezing rain occurs when supercooled liquid droplets strike the subfreezing surface. If temperatures are colder than -10°C, liquid droplets gradually refreeze and either snow or sleet occurs dependent on the depth of the cold air. Partial melting of the snow leaves an ice crystal surrounded by liquid. Immediately upon reentering subfreezing air, refreezing occurs resulting in

ice pellets. Droplet melting/refreezing are affected by droplet size distributions and compositions, vertical motions, radiative effects, diabatic processes, and other less significant processes. These are described in detail by Raga et al (1991).

Critical thickness is also used to forecast freezing precipitation and ice pellets. Keeter and Cline, 1991 found that a 1000-850mb thickness of 1280-1290m is associated with ice pellets while a thickness of 1290-1310m indicates freezing rain. In both the freezing rain and ice pellets situations, the authors note that the critical 850-700mb thickness is 1540-1570m. Bachand, 1986 found a critical 1000-850mb thickness of less than 1290m would result in ice pellets. The author notes that a 850-700mb thickness of 1540m is associated with freezing rain and ice pellets.

1.3 Research Goals

The primary goals of this research are:

• Provide a powerful but easy-to-use supplement to the NGM MOS by improving upon and expanding the LOG/PT technique utilized operationally by the National Weather Service Forecast Office (NWSFO) in Raleigh, North Carolina.

• Develop a simple set of regression equations and nomograms to nowcast/forecast accumulating frozen and freezing precipitation. The regression equations provide a conditional probability of frozen or freezing precipitation. Nomograms allow the forecaster to descriptively differentiate amongst various precipitation sub-types (e.g., mixed liquid but non-accumulating frozen, all snow versus mixed accumulating frozen).

- Use a partial thickness approach, for simplicity, supplemented with additional predictor values (temperature, humidity, wind speed/direction at various levels) when they are significant.

- Provide critical thickness values for frozen, mixed, and freezing precipitation.

- Illustrate the operational use of the technique by means of a case study.

2 TYPE OF PRECIPITATION: DESCRIPTIVE AND OBJECTIVE GUIDANCE

2.1 Overview

The Type of Precipitation: Descriptive and Objective Guidance (*TOP DOG*) consists of regression equations and nomograms for both single stations and regions. Regression equations provide objective guidance in the form of conditional probabilities of either frozen or freezing precipitation during the forecast period. Nomograms provide an objective and descriptive guidance for the specific or mix of precipitation types expected. TOP DOG is designed for operational use by forecasters in the southeastern United States.

The TOP DOG technique allows the forecaster to forecast precipitation type over a 6 hour period (forecast period) through the use of thickness values and/or other atmospheric variables (e.g. temperatures at various levels) from radiosonde observations (RAOBS) and/or predicted values from numerical weather prediction models such as the Nested Grid Model (NGM). TOP DOG consists of single station and regional regression equations for the conditional probability of accumulating (more than a trace) frozen or freezing precipitation versus liquid precipitation. Probabilities are conditional on the occurrence of precipitation and are known as conditional probabilities. Regional and single station nomograms may be used operationally, in concert with or independent of the conditional probabilities from the regression equations, to descriptively forecast overall precipitation type (rain, ice pellets, snow, or freezing rain) or to discriminate amongst mixed (e.g. rain

and snow, freezing rain and snow, etc.) precipitation cases. *TOP DOG* was developed from the upper air and surface climatic databases (1973-1991) for a total of nine stations and two regions.

TOP DOG is designed to supplement, not replace, NGM MOS, current local forecast techniques, or a thorough understanding of local and regional influences that determine precipitation type. Forecasters are encouraged to use *TOP DOG* as a part of their comprehensive forecast development process.

TOP DOG differs significantly from the 'snapshot' approaches of the NGM MOS (see Erickson, 1994) and Heppner's (1992) 'Magic Numbers'. It is a forecast over a period ending 6 hours after the input data time. For example, a forecast period ending at 0600Z for a 0000Z sounding. Heppner's 'Magic Number' technique and the NGM MOS are forecasts valid at a specified point in time (i.e. 0600Z). The snapshot forecast is not intended to be used to directly infer the precipitation types falling during the period between two forecasts. Erickson notes that the NGM MOS users should use the trends of probabilities, in space and time, to truly 'forecast' transitions amongst precipitation types. NGM MOS, unlike TOP DOG, includes ice pellets in its freezing rain regression equation. TOP DOG allows for a conditional probability of freezing precipitation or frozen precipitation forecast and/or a nomogram based forecast differentiating amongst as many as 8 possible precipitation subtypes described in detail later. The NGM MOS does not provide the forecaster the specificity to characterize operationally significant mixed (e.g. freezing rain with nonmeasurable frozen) precipitation event. For example, the

ability to differentiate between ice pellets and freezing rain or freezing rain or accumulating frozen precipitation is critical to the general public, government, and private enterprise. The NGM MOS provides a quasi-'black box' type forecast involving dozens of predictors, many transparent or unavailable to the forecaster. The complexity and number of predictors make it difficult for the forecaster to fully investigate each predictor and the effect of model difficulties on the MOS forecast. TOP DOG provides the forecaster with a simpler understanding of the atmospheric conditions (e.g. warm air advection between 850-700mb, cold air damming in the level from the surface to 950mb) leading to changes of precipitation type through the use of a graphical tool, the nomogram. TOP DOG is designed for the particular cold air damming situations that are troublesome to the NGM and the derived NGM MOS.

The Local Objective Guidance for Predicting Precipitation Type (LOG/PT) is currently used operationally by the NWSFO in Raleigh to forecast precipitation type (See Keeter and Cline, 1991) and provided an impetus to the development of TOP DOG. LOG/PT is a forecast for a 12-hour period versus TOP DOG's 6-hour forecast period. Unlike TOP DOG however, LOG/PT uses a linear approximation to the logit curve. This approximation, although anchored to definite frozen and freezing thresholds, leads to underforecasting frozen precipitation at low (i.e. cold) thickness values and overforecasting at high (i.e. warm) thicknesses. LOG/PT does not provide a regression equation for freezing precipitation and is less specific in its

defined precipitation subtypes. TOP DOG expands on LOG/PT's data base and expands the general approach to the entire southeastern United States.

2.2 Data Set

Surface and upper air data for the winter months (November through March) during the period of 1973-1991 inclusive were included in the appropriate data set. Suspect data (i.e. poor quality, missing information, suspicious data, etc.) were not included in this analysis. This will be further discussed in § 2.4.3 and 2.4.4. An additional reduction in the upper air data set was due to the non-availability of 0600 and 1800Z radiosonde soundings since radiosondes are routinely launched only twice daily (0000Z and 1200Z). Also, a significant number of upper air observations are missing. Additionally, surface data are filtered to include only those periods involving precipitation. The research development data set consists of a merging of the upper air and surface data set variables. Cases not contained in both data sets (surface and upper air) were not included in the development data set. TOP DOG's regression equations and nomograms were developed from the 1973-1991 development data set for the southeastern United States and area surrounding that region.

Data for the case study (See Chapter 4) does include additional radiosonde launches at 06000Z and 1800Z. The case study data set was not included in the development data set.

Figure 2.1 shows the stations used in this the development of this technique. Coastal stations and stations located in or west of the Appalachian Mountains were included for comparison.

Table 2.1 shows the TOP DOG stations where surface and upper air observations were collocated hence providing a high degree of confidence that thickness values and temperatures derived from the upper air sounding information is representative for the airmass above and surrounding the station.

Raleigh-Durham (RDU) is the only station where surface and upper air observations were not collocated. RDU was included for comparison with previous techniques (particularly Keeter and Cline (1991)) and is tied to the Greensboro (GSO) upper air sounding data. RDU is relatively close to GSO (approximately 72 km) hence the upper air information from the GSO sounding is fairly representative of the atmosphere at Raleigh-Durham.

Table 2.2 indicates the regional groupings used throughout TOP DOG. Nashville, TN (BNA), Wallops Island, VA (WAL), and Huntington, WV (HTS) were not included in regional groupings. Stations in the Southeastern United States Piedmont region (PIEDMONT) were located in the climatological cold air damming region as defined by Bell and Bosart (1988) and have virtually the same elevation. southeastern United States coastal stations (COASTAL) are near and often influenced by the Gulf Stream and are 4m or less in elevation.

STATION NAME	*ICAO*
Athens, GA	AHN
Cape Hatteras, NC	HAT
Charleston, SC	CHS
Greensboro, NC	GSO
Huntington, WV	HTS
Nashville, TN	BNA
Sterling, VA	IAD
Wallops Island, VA	WAL

Table 2.1. Stations in the study where surface observations and upper air observations are collocated. ICAO is include for ease of reference throughout this thesis.

PIEDMONT	*COASTAL*
Athens, GA (AHN)	Charleston, SC (CHS)
Greensboro, NC (GSO)	Cape Hatteras, NC (HAT)

Table 2.2. TOP DOG's Regional alignment.

2.3 Precipitation Type and Subtypes

Operationally, the subtypes in Table 2.3 are designed to provide the forecaster with an improved ability to describe operationally significant changes in precipitation type. Operationally significant accumulations of precipitation are those greater than a trace (>=.05" liquid equivalent, 1" of snow/frozen, 0.5" ice pellets). Measurable precipitation in this study is defined as greater than a trace of precipitation.

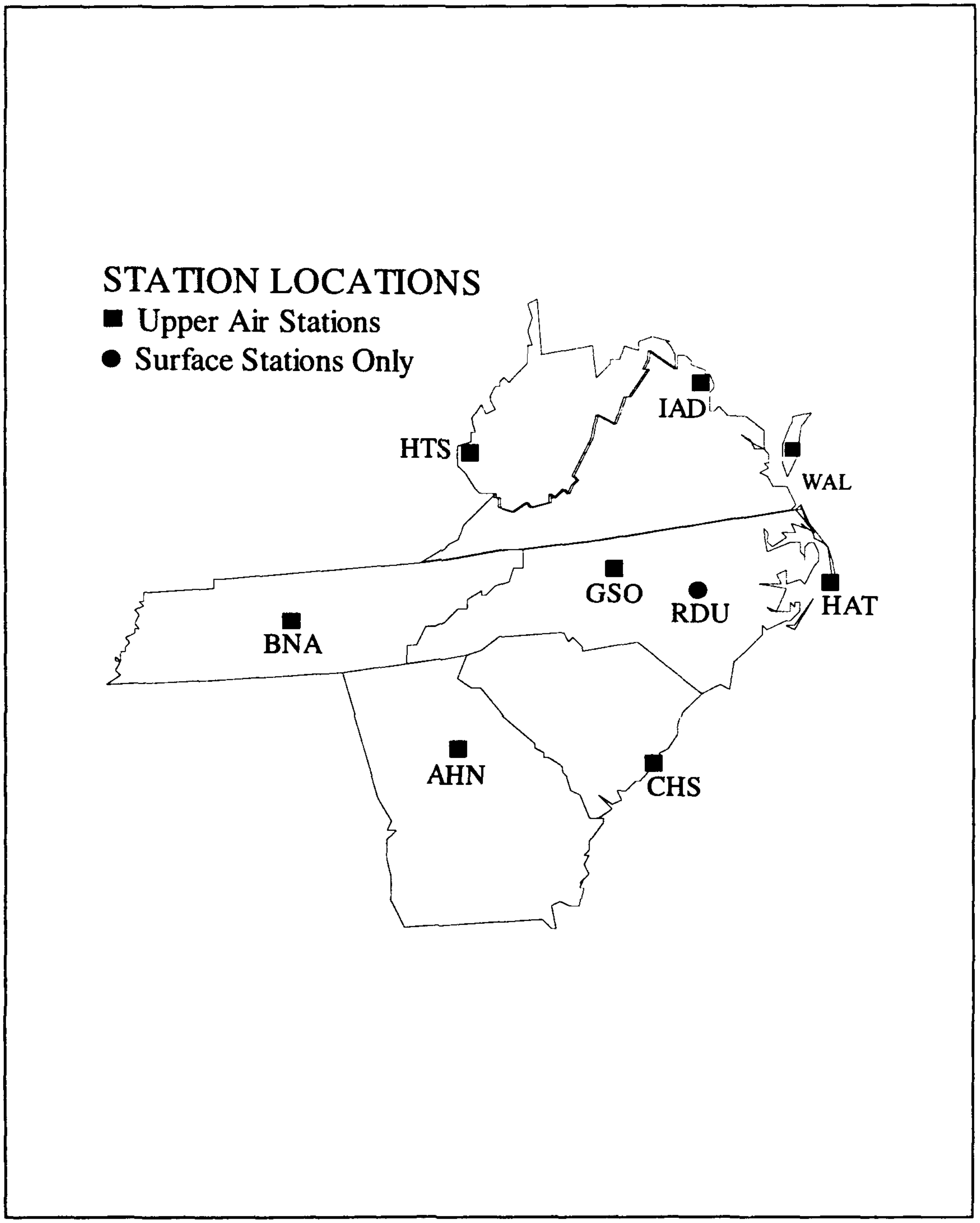

Figure 2.1. The southeastern United States and stations used in development of TOP DOG. □ indicated stations where surface and upper air observations are collocated. • is the station where surface and upper air observations are not collocated.

Forecasters will be able to use TOP DOG's nomograms to specify the precipitation types and subtypes expected during the 6-hour forecast period. The subtypes defined here are an expansion and a refinement of the precipitation subtypes defined by Keeter and Cline (1991). TOP DOG's subtypes tell the forecaster where to place emphasis in the forecast. For example, whether to emphasize measurable frozen precipitation or freezing precipitation during a mixed precipitation event. Currently, the forecaster must subjectively determine the emphasis from the MOS's trends of precipitation type. Appendix 1 provides the forecaster with sample forecasts for each precipitation subtype.

Table 2.4 shows the delineation of the wintry precipitation type as used in TOP DOG's regression portion. Note that ice pellets are included in the frozen category since forecast customers prepare for and handle an accumulation of ice pellets similar to an accumulation of snow. Whenever the term mixed is used it indicates that numerous types of precipitation (i.e. snow, ice pellets, freezing rain/drizzle, and/or rain) are occurring simultaneously or precipitation type changes during the forecast period. Frozen precipitation is defined as a measurable accumulation of a frozen form of precipitation (snow and/or ice pellets). In general, precipitation cases included in the data set were:

- Frozen precipitation includes both snow and ice pellets. Operationally, it is used interchangeably with snow.
- Freezing precipitation is defined as freezing rain or freezing drizzle.

• Liquid precipitation includes rain and drizzle and is used interchangeably with rain.

SUBTYPE	DESCRIPTION {SYMBOL}	CRITERIA
1	All Snow {*}	Measurable snow/ Snow only
2	Mixed Frozen {X}	Measurable mixed frozen /Various Precipitation Types
3	All Ice Pellets (a.k.a. Sleet) {Δ}	Measurable ice pellets/ Sleet only
4	Freezing Rain mixed with Frozen {Y}	Trace or less mixed frozen, snow or ice pellets/measurable liquid equivalent/Various types but no rain
5	All Freezing Rain {Z}	Measurable Liquid equivalent/Freezing rain/drizzle only
6	Mixed Liquid with Freezing Rain {#}	Trace or less of mixed frozen, snow, or ice pellets/Measurable liquid equivalent/Various types mixed with rain and freezing rain.
7	Mixed Liquid {+}	Trace or less mixed frozen, snow, or ice pellets/Measurable liquid Equivalent/Various types but no freezing rain
8	All Rain {•}	Measurable rain/ rain only

Table 2.3. Definitions and symbols of Precipitation Subtypes in TOP DOG Nomograms. Measurable is defined as greater than or equal to .05" of liquid equivalent (i.e. 1" {>2.5cm} of snow or mixed frozen, or .5" (>1cm) of ice pellets) during the 6-hour period.

TYPE	DESCRIPTION {SYMBOL}	SUBTYPES
1	Frozen Precipitation {*}	All Snow, All Sleet, Mixed Frozen
2	Freezing Precipitation {Z}	All Freezing Rain, Freezing Rain mixed with Frozen
3	Liquid Precipitation {•}	All Rain, Mixed Liquid, Mixed Liquid with Freezing Rain

Table 2.4. Definitions and Symbols of Precipitation Types used as Predictands in Regression as Defined by Included Subtypes.

2.4 Experimental Design: REGRESSION

2.4.1 Overview

The logit regression model is often used to relate a binary response variable (the occurrence or nonoccurrence of an event) to multiple explanatory variables. TOP DOG's binary responses are frozen precipitation versus liquid precipitation and freezing precipitation versus liquid precipitation. Regression equations based on the logit model were developed for each station and region. Tests of statistical significance were used to simplify the statistical models used for prediction.

The regression portion of TOP DOG provides a conditional probability forecast of binary response variables (occurrence or nonoccurrence of an event). The binary response variables are frozen versus liquid precipitation and freezing versus liquid precipitation. The logit curve for a single potential predictor has the form:

$$EY = p = \left(1 + e^{-(\beta_0 + \beta_1 X)}\right)^{-1} \tag{2.1}$$

where EY is the expected value of Y or the probability (p) of an occurrence of frozen or freezing precipitation (values of 0 to 1), β_0 is the intercept, β_1 is the slope parameter, and X is the potential predictor. (See Erickson et al, 1993). The linear logistic model has the form:

$$\mathrm{logit}\,(p) = \ln(p/(1-p)) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots\ldots + \beta_n X_n \tag{2.2}$$

where p is the conditional probability of either frozen or freezing precipitation, β_0 is the intercept, and $\beta_1 \ldots\ldots \beta_n$ are the slope parameters or coefficients associated with each potential predictor (X). (SAS, 1990; Cox and Snell, 1989; and Glahn and Bocchieri, 1975). Inverting the logit transform using equation 2.3 provides the user with a conditional probability of the binary response variable.

$$p = \exp[\text{logit}(p)] / (1+\exp[\text{logit}(p)]) \qquad (2.3)$$

Figure 2.2 shows the logit curve of the conditional probability of snow for Greensboro, NC versus the 1000-850mb thickness. As expected the estimated conditional probability of snow increases as the 1000-850mb thickness decreases. "Froze" is a binary predictand for frozen precipitation. Values of 1 for froze indicate that frozen precipitation occurred. Conversely, a value of 0 for froze indicates that liquid precipitation occurred. Applying the Keeter and Cline (1991) linear approximation to the logit curve, even though it is anchored to definite frozen or liquid values, would result in overforecasting frozen precipitation at higher thickness values and underforecasting frozen precipitation at lower thickness values.

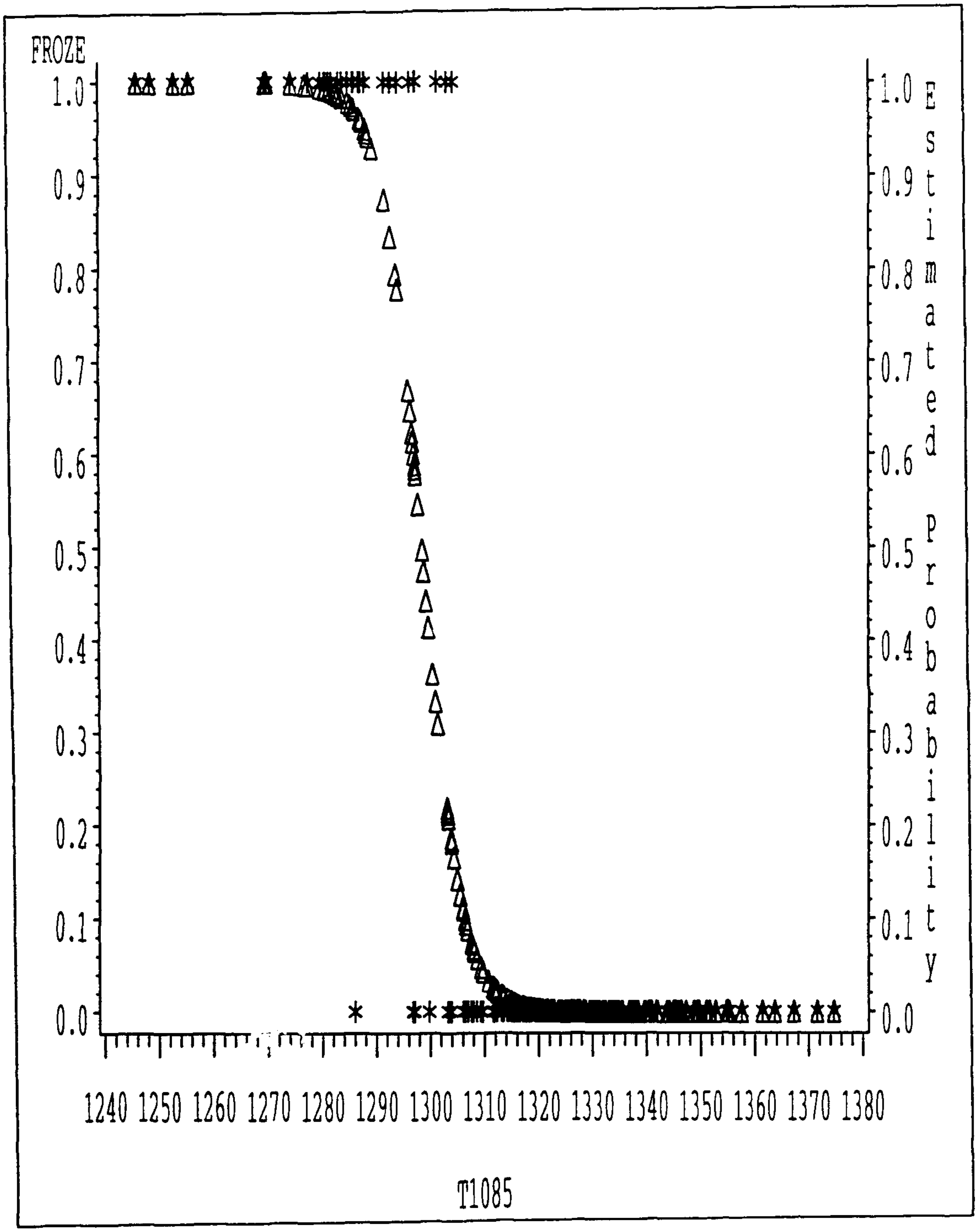

Figure 2.2 The binary response variable froze and the predicted probability of frozen precipitation from the logit transformation of the thickness (m) between 1000-850mb. Stars denote values of froze while triangles denote predicted values of froze or the estimated probability of frozen precipitation.

2.4.2 Predictands (Surface Data Set)

Surface data for the stations listed in Tables 2.1 and 2.2 for the period 1973-1991 (November through March) were included in this research. Data were encoded in the USAF's DATSAV2 format and included quality control flags. Flags for each type of wintry precipitation (i.e. rain/drizzle, snow, ice pellets, freezing rain/drizzle) were set for each hour. For example, in hour 1 only snow fell. Thus the snow flag was raised; then in hour 2 only rain fell. Thus the rain flag was raised. If more than one precipitation type fell during any hour flags for those types would be raised. To be included in the data set, each individual case required that precipitation type be indicated during each hour of the forecast period. Six-hour precipitation amount (liquid equivalent and snowfall) was used to filter non-operationally significant (no measurable liquid equivalent) precipitation events. Cases included in the development of TOP DOG's regression equations and nomograms, the observations in the 6-hour period following the radiosonde, were required to meet the following criteria:

- A minimum of 1 hourly observation in the period with a surface temperature of <=+7°C. (Rules out definite rain cases).
- At least 1 hourly observation during the period with a surface dewpoint of <=+4°C. (Rules out definite rain cases).

- A minimum of .05"(liquid equivalent) of precipitation. Precipitation subtypes defined in Table 2.3 meet this criteria. (Eliminate nonoperationally significant events).
- During the 6 hour period, precipitation type/weather was reported each hour. (Reduce or eliminate errors in categorizing precipitation type).

2.4.3 Predictors (Upper Air Data Set)

Upper air data for the stations listed in Tables 2.1 and 2.2 for the period 1973-1991 were included in this research. Data was encoded in the USAF's Upper Air DATSAV2 format and included quality control flags. Table 2.5 lists the variables extracted from or derived from the upper air data set for inclusion in the development data set. These variables are also the potential predictors of precipitation type used in TOP DOG. Encoding errors in the data set precluded use of relative humidities at 900 and 850mb. Additionally, wind speeds and directions above 850mb were limited and of suspect quality. No wind data above 850mb was used. The upper air data set was merged with surface data set (period ending 6 hours after the upper air data). Note that most cases include in the data set fell in the 0000-0600Z and 1200-1800Z periods since radiosondes are not routinely released at 1800 and 0600Z.

Thickness (Layer mb)	*Temperatures*	*Relative Humidity*	*Wind Speed/Direction*
1000-500	Surface	Surface	950
1000-700	950	950	900
1000-850	900	700	850
1000-900	850		
1000-950	700		
950-850	500		
900-850			
850-700			
700-500			

Table 2.5. Variables extracted or derived from the upper air data set as potential predictors of precipitation type.

2.4.4 Assessing Model Fit

A method to rank competing models is required to determine the most effective models at forecasting either frozen or freezing precipitation. The criterion used to assess model fit are the -2 Log Likelihood (LOG, Equation 2.4), the Akaike Information Criteria (AIC, Equation 2.5), and the Schwartz criterion (SC, Equation 2.6). (SAS, 1990). Under the null hypothesis that all the possible explanatory variables entered into the model are zero, LOG has a chi-square distribution. The AIC and SC criteria are simply two different ways of adjusting LOG for the numbers of terms in the model and the number of observation in the research data set. The above criteria are designed to compare the 'fit' of various models that use the same data set. The lower the score the more desirable the prediction model (SAS, 1990).

$$-2 \text{ Ln } L = \text{LOG} = -2 (\ln \hat{p}_0 + \ln \hat{p}_1) \qquad (2.4)$$

where $\hat{p}_0$ is the estimated probability of a nonoccurrence, L is the likelihood, and $\hat{p}_1$ is the estimated probability of an occurrence obtained by replacing β with the maximum likelihood estimate.

$$\textbf{Akaike Information Criterion:}\ \ AIC = LOG + 2(2+s) \qquad (2.5)$$

where s is the number of explanatory variables.

$$\textbf{Schwartz Criterion:}\ \ SC = LOG + (2+s)\ln(N) \qquad (2.6)$$

where s is as defined for AIC and N is the total number of observations.

The sensitivity of a given statistical forecast model, known in the operational forecasting community as the probability of detection (POD) is defined as the proportion of frozen or freezing cases predicted to be frozen or freezing. (POD=Predicted cases/actual cases). The false positive rate (FPR), known operationally as the false alarm rate/ratio (FAR) is the proportion of predicted frozen or freezing cases that were observed as liquid cases. (FPR=FAR= Predicted cases observed as liquid cases/predicted cases). The false negative rate (FNR), known operationally as the bias (BIAS), is the proportion of predicted 'no cases' that are observed as 'cases'. (FNR=BIAS= actual cases/cases not predicted). (SAS, 1990; and Keeter and Cline 1991).

2.4.5 Testing the Significance of Potential Predictors

The operational forecaster wants a forecast scheme for precipitation type that is simultaneously powerful yet easy and quick to use. Meeting this goal while keeping the forecaster aware of the most important physical process has challenged

many a researcher. Erickson (1994) Heppner (1992) and Keeter and Cline (1991) are amongst the most recent attempts. There is a danger in oversimplification of the procedures or models used to forecast any phenomena, including precipitation type. This research attempts to overcome this hurdle by utilizing tests of statistical significance to determine if an additional predictor really adds to the ability of model to forecast freezing or frozen precipitation. As a means of simplification, thicknesses used traditionally and understood by the operational forecaster provided the base upon which this technique is built. Unlike the NGM MOS, TOP DOG includes and tests the significance of additional predictors (i.e. temperatures, winds, etc. at various levels of the atmosphere) only after thickness values were included.

Tests of significance were used to simplify and design proposed explanatory forecast models. TOP DOG uses significance tests to show whether or not more sophisticated models significantly improve simpler models. For example, does the subdivision of the traditional 1000-500mb thickness into partial thicknesses improve the forecasting of frozen precipitation?

An illustration of the tests of the statistical significance of potential (partial thicknesses) predictors used by this technique follows. Assume we want to test whether a more complex model $\{Y=\beta_0+\beta_1X_1+\beta_2X_2\}$ is statistically better than a simpler model $Y=\beta_0+\beta_1(X_1+X_2)$. Accepting the hypothesis that $\beta_1=\beta_2$ indicates that the complex model is not significantly better than the simpler model. Tests of this hypothesis were accomplished by using the test model $Y=\beta_0+\beta_1(X_1+X_2)+\beta_2^*X_2$

where $\beta_2^* = \beta_2 - \beta_1$. For example, let X_1 = 1000-700mb thickness (T1070) and X_2 = 700-500mb thickness (T7050), so that $X_1 + X_2$ = 1000-500mb thickness (T1050). A test of the hypothesis that $\beta_2^*=0$ is used to determine if the more complex model is significantly better (using Chi-square tests at the appropriate level {.05 for this research}) than the simpler model. . If the researcher rejects the hypothesis that $\beta_2^*=0$ then the more complex model is a statistically significant improvement over the simpler model. If however, the researcher fails to reject that hypothesis, then the more complex model is not significantly better than the simpler model. Additional potential predictors (X_n) are added one at a time using a forward selection procedure. The hypothesis that $\beta_n^* = 0$ is tested for each n. (Berger, 1994).

Tests of significance were used to confirm the significance of all potential predictors and the adequacy of the proposed explanatory models. Using the 1000-500mb thickness (T1050) as the starting point, subdivisions into partial thicknesses (e.g. the 1000-700 mb thickness {T1070) and the 700-500 mb thickness{T7050}) were undertaken and tested. Further subdivisions of the lower level thicknesses such as the 1000-700 mb thickness into the 1000-850 mb (T1085) and 850-700 mb (T8570) partial thicknesses were accomplished in a similar manner. Additional subdivisions of the 1000-850 mb thickness into either the 1000-950 (T1095) or 1000-900 mb (T1090) and 950-850 (T9585) or 900-850 (T9085) mb partial thicknesses were used to test whether inclusion of these thicknesses would be

statistically significant. After inclusion of all thicknesses, all other potential predictors (See Table 2.5 for a list) were tested to ascertain their ability to improve the effectiveness of the model. Simplification of the model while maintaining its power required that TOP DOG include only those variables that provided a statistically significant improvement in the model's ability. Tests of significance were undertaken independently for both the prediction of freezing precipitation and frozen precipitation. A summary of the tests of significance are found in Tables 2.6 and 2.7 for frozen precipitation and Tables 2.8 and 2.9 for freezing precipitation. Appendix 2 lists numbers of cases of frozen/freezing precipitation for each station used in this analysis.

Keeter and Cline (1991) used subdivision of the 1000-700 mb thickness into the 1000-850 and 850-700mb partial thicknesses to forecast wintry precipitation. They further state that while the 1000-500mb thickness is the traditional means to differentiate precipitation type, the 1000-700 mb thickness is more representative of the thermal structure of the atmospheric level through which precipitation type is determined. They hypothesize that further subdivision of the 1000-700 mb thickness should improve the ability of a model to forecast precipitation type, particularly freezing precipitation. Erickson (1993 and 1994) along with Dallavalle et al (1992) and Bocchieri and Maglaras (1983) note that the NGM MOS uses partial thickness that subdivide the 1000-700 mb thickness to predict both frozen and freezing precipitation.

This research's tests of significance (summarized in Table 2.6) for the prediction of frozen versus liquid precipitation at single stations in the southeastern United States showed that further subdivision of thicknesses (e.g. 1000-700 mb) into partial thicknesses after subdivision of the 1000-500 mb thickness into the 1000-700 and 700-500 mb thicknesses usually did not improve the models forecasting capability. The lack of significance of further subdivision of thicknesses does not prove that the state of the atmosphere in the lowest part of the troposphere nearest the surface is not important. The 1000-700 mb (surface to about 10K feet) thickness appears to sufficiently take into account the section of the atmosphere where snow forms and falls. Inclusion of all non-thickness potential predictors in the model adds additional complexity to the model that is not required to produce a quality forecast of frozen precipitation at these stations. The mountain station (HTS) showed that the atmosphere below 850mb is important for higher elevations. The inclusion of the lower thicknesses (e.g. 1000-850.850-700 mb thicknesses) did not statistically improve the frozen precipitation forecast models for other stations.

Regionally, for predicting frozen precipitation at inland SEUS stations (GSO/AHN), the addition of the 500 mb temperature after inclusion of all partial thickness (using either T1090 or T1095 as a base) was barely significant (see Table 2.7). While further subdivisions of thickness (after the 1000-700 and 700-500 mb partial thickness) were not significant for the SEUS, they were significant for the coastal stations (CHS/HAT) in the region. Subdivision of the 1000-700 mb thickness into the 1000-850 and 850-700 mb thickness was important for coastal

regions. The 1000-850 mb thickness takes into account the strength of cold air in the lower levels and while also including the "warm" air overrunning the cold air dam, while the 850-700 mb thickness explains some of the strength of warm air advection and whether the atmosphere is cold enough to maintain snow/frozen precipitation. The temperature at 500mb may provide an insight into the location of the upper level trough. The following is proposed: If the temperature at 500mb is relatively high, the trough is typically to the west, If relatively low, the trough is roughly overhead.

For freezing precipitation, tests of significance showed that subdivision of the 1000-700mb thickness and the 1000-850 mb thickness were significant for the forecasting of freezing precipitation at stations in the southeastern United States. Bell and Bosart (1988) and Forbes et al (1987) note that the cold air dammed along the eastern slopes of the Appalachian mountains extends upward to approximately 930 mb. Obviously, the 1000-950 mb thickness and the 1000-900 thickness represent the strength and depth of the cold air damming for inland stations in the region.

Regionally (See Table 2.9), the temperature at 950mb was significant. Again, the temperature at 950mb represents the strength and depth of the cold air dammed along the eastern slopes. No other potential predictors were significant.

Additional Complexity Tested	AHN	HAT	CHS	GSO/ RDU	HTS	BNA	IAD	WAL
T1050	Sig	Sig	Sig	Sig	Sig	Sig	Sig	Sig
T1070 T7050	Sig	Not Sig	Not Sig	Sig	Sig	Sig	Sig	Not Sig
T1085 T8570	Not Sig	Not Sig	DNC	Not Sig	Sig	Not Sig	Not Sig	Sig
T1095 T9585	Not Sig	Not Sig	DNC	Not Sig	Sig	Not Sig	Not Sig	Not Sig
T1090 T9085	Not Sig	Not Sig	DNC	Not Sig	Not Sig	Not Sig	Not Sig	Not Sig
Additional Non-thickness Potential Predictors	None Sig	None Sig	DNC	None Sig	None Sig	None Sig	None Sig	None Sig

Table 2.6. Frozen Precipitation. Summary of tests of statistical significance for individual stations. Sig indicates the partial thicknesses (more complex model) indicated were significant. No Sig indicates that the partial thicknesses did not improve the simpler model. DNC shows that the test was inconclusive since too few cases did not allow the model to converge and therefore no β_n^* could be tested.

	PIEDMONT	COAST
T1050	Sig	Sig
T1070 T7050	Sig	Sig
T1085 T8570	Not Sig	Sig
T1095 T9585	Not Sig	Not Sig
T1090 T9085	Not Sig	Not Sig
Additional Potential Predictors	Temp 500	Temp 500

Table 2.7. Frozen Precipitation, Regional approach otherwise same as Table 2.6.

	AHN	HAT	CHS	GSO/ RDU	HTS	BNA	IAD	WAL
T1050	Not Sig	DNC	DNC	Sig	Sig	Not Sig	Not Sig	Not Sig
T1070 T7050	Sig	DNC	DNC	Sig	Not Sig	DNC	Sig	Not Sig
T1085 T8570	Sig	DNC	DNC	Sig	Sig	DNC	Sig	DNC
T1095 T9585	Not Sig	DNC	DNC	Sig	Not Sig	DNC	Sig	DNC
T1090 T9085	Not Sig	DNC	DNC	Sig	Sig	DNC	Sig	DNC
Additional Potential Predictors	None Sig	DNC	DNC	None Sig	None Sig	DNC	None Sig	DNC

Table 2.8. Freezing Precipitation otherwise same as Table 2.6.

	PIEDMONT	COAST
T1050	Not Sig	Sig
T1070 T7050	Sig	Not Sig
T1085 T8570	Sig	DNC
T1095 T9585	Sig	DNC
T1090 T9085	Sig	DNC
Additional Potential Predictors	Temp 950	DNC

Table 2.9. Freezing Precipitation, Regional approach. Same as Table 2.7

2.4.6 Proposed Explanatory Models

After inclusion of thicknesses and subdivisions of the 1000-500mb thickness and its partial thicknesses into additional partial thicknesses, only the temperatures at 500mb (frozen precipitation) and 950mb (freezing precipitation) provided a significant improvement to the forecast model. Table 2.10 lists the precipitation type prediction models tested. The traditional model is, as its name implies, used to exemplify the traditional precipitation type (particularly frozen precipitation) forecast model. The traditional plus model is included as a gage of the operational improvements used by operational forecasters (recall Keeter and Cline (1991)). The Keeter model is the model used extensively by Keeter and Cline (1991) to improve the ability of the NWSFO at Raleigh-Durham, NC to forecast mixed frozen (regression) and freezing precipitation (nomogram used for this differentiation). The NGM MOS (Erickson, 1993 and 1994) also uses the logit transformation of the partial thicknesses included in the 'Keeter' model. Two potential models (Souza1 and Souza2) are proposed to explain the effect of cold air damming on precipitation type in the southeastern United States. The Souza1 and Souza 2 models were run with and without the temperature at 500mb for frozen precipitation and the temperature at 950mb for freezing precipitation. Inclusion and exclusion of the temperatures in these models may allow the research to account for and measure the importance of the location of the upper level trough for frozen precipitation and the strength (i.e. the relative coldness of the airmass dammed east of the mountains) of cold air damming for freezing precipitation.

Forward selection (referred to as stepwise regression by Erickson (1993 and 1994), Keeter and Cline (1991), etc.) of variables was used to simplify the proposed models. The goal of TOP DOG is to provide a powerful yet simple tool to forecast precipitation type. Forward selection allows for the elimination of variables in the model that do not significantly improve the forecast ability of that model. The intercept is the first variable entered into the model. The model then adds the most statistically significant variable, if any, to the model and recalculates the chi-squares used to test for significance. This step continues until no further variable in the proposed model meets the statistically significant threshold (α=.05 in this research). For example, the Keeter model simplifies to only the 1000-850mb thickness for the prediction of frozen precipitation. The Souza1 and Souza1B models for the prediction of frozen precipitation have the same form after forward selection. (i.e. temperature at 500mb was found not to be significant). Chapter 3 contains the results of this process for GSO and the SEUS.

Model Name	Statistical Model
Traditional Model	Logit (p)= $\beta_0 + \beta_1 T1050$
Traditional Plus Model	Logit (p) = $\beta_0 + \beta_1 T1070 + \beta_2\ T7050$
Keeter Model	Logit (p) = $\beta_0 + \beta_1 T1085 + \beta_2 T8570 + \beta_3 T7050$
Souza1 Model	Logit (p) = $\beta_0+\beta_1 T1095+\beta_2 T9585+\beta_3 T8570+ \beta_4 T7050+ \beta_5 temp500/temp950$
Souza1B Model	Logit (p) =$\beta_0+\beta_1 T1095+\beta_2 T9585+\beta_3 T8570+ \beta_4 T7050$
Souza2 Model	Logit (p) =$\beta_0+\beta_1 T1090+\beta_2 T9085+\beta_3 T8570+\beta_4 T7050 + \beta_5 temp500/temp950$
Souza2B Model	Logit (p) =$\beta_0+\beta_1 T1090+\beta_2 T9085+\beta_3 T8570+\beta_4 T7050$

Table 2.10. Proposed explanatory models. The letter T indicates thickness between the two layers in meters (i.e. 1090 is the 1000-900mb layer). T1090 therefore is the thickness between 1000 and 900mb. Temperature is abbreviated temp, is in degrees Celsius and is for the level indicated (mb). Temperatures at 500mb was used in the Souza models for frozen precipitation, temperature at 950mb for freezing precipitation.

2.4.7 Models Sensitivities from Proposed Explanatory Models

Tables 2.11 and 2.12 summarize the sensitivities or probability of detection (as defined in 2.6.5) for the forecasting of frozen precipitation produced by the proposed models. Freezing rain forecast sensitivities or probability of detection are summarized in Tables 2.13 and 2.14. A conditional probability threshold of 50% was used to differentiate forecasts of frozen precipitation from forecasts of liquid precipitation. The threshold was lowered to 40% for freezing precipitation forecasts.

Model Name	AHN	HAT	CHS	GSO	HTS	BNA	IAD	WAL
Traditional Model	45.5	0	33	43	46.8	42.9	65.1	42.9
Traditional Plus Model	54.5	0	66.7	86.7	43.1	81	93	85.7
Keeter Model	63.6	25	66.7	90	60.6	81	93	71.4
Souza1 Model	63.6	25	66.7	86.7	52.3	71.4	93	71.4
Souza1 Model, NO 500mb Temperature	63.6	25	66.7	86.7	52.3	71.4	93	71.4
Souza 2 Model	63.6	25	66.7	93.3	52.3	71.4	93	71.4
Souza2 Model, No 500mb Temperature	63.6	25	66.7	93.3	52.3	71.4	93	71.4

Table 2.11. Summary of Frozen Precipitation sensitivities or probability of detection for tested models at individual stations. Sensitivities (PODs) are given in % {POD=Predicted case (conditional probability of >= 50%)/actual cases)}

Model Name	PIEDMONT	COAST
Traditional Model	39	14.3
Traditional Plus Model	78	28.6
Keeter Model	85.4	42.9
Souza1 Model	80.5	28.6
Souza1B Model, NO 500mb Temperature	80.5	28.6
Souza 2 Model	82.9	42.9
Souza2B Model, No 500mb Temperature	80.5	42.9

Table 2.12. Frozen Precipitation, Regional approach otherwise same as Table 2.11

Tables 2.11 and 2.12 clarify the results found from the tests of significance (See 2.6.6 for details of tests). Unlike the tests of significance described in § 2.6.6, model simplification by forward selection often resulted in a

reliance on low-mid level thickness values. Overall, the probability of detection of frozen precipitation was improved as measured by sensitivity (POD) by the inclusion of low level partial thickness while excluding upper level thicknesses (e.g. T7050). Results for the same models when all model variables are used reiterated the findings from the tests of significance. Stations affected by cold air damming (AHN, GSO, and to a lesser extent IAD) showed a marked improvement when models that included the portions of the atmosphere affected by cold air damming are included. A slight improvement (i.e. a decrease in its value) is found in the Schwartz Criterion for the Keeter and Souza models. This indicates that while the partial thicknesses do not provide a statistically significant improvement when all variables are include, they do provide a slight improvement in the model's fit.

Frozen precipitation is relatively rare along the coast in the Southeastern United States. Higher confidence is found in the regional output due to an increased number of case enhancing the stability of the models. (See Appendix 2). A slight improvement was provided by the inclusion of the 1000-850 mb thickness. Additional partial thicknesses provide no improvement.

BNA's results were very similar to those in the cold air damming region. One might believe based on operational practice that cold air is also dammed on the west side of the Appalachian Mountains. Unlike the eastern slopes of the Appalachian Mountains, cold air damming on the western slopes is of a much shorter duration primarily due to the orientation of the mountains and the mountain parallel (southerly) direction warm air advection in this region. On the eastern

slopes, warm air advection initially occurs perpendicular to or at an angle to the mountains. (Keeter and Cline 1991).

HTS's results are similar to BNA's but since HTS is of a higher elevation, the information provided by the Souza models is not as informative. Much of the information provide by the lower levels of the Souza models is located below the surface at HTS.

Model Name	AHN	HAT	CHS	GSO	HTS	BNA	IAD	WAL
Traditional Model	0	DNC	0	0	0	0	0	0
Traditional Plus Model	12.5	DNC	0	54.5	0	0	7.1	0
Keeter Model	50	DNC	DNC	72.7	0	66.7	14.3	0
Souza1 Model	62.5	DNC	DNC	74.2	0	0	27.3	DNC
Souza1 Model, NO 500mb Temperature	62.5	DNC	DNC	80.6	0	DNC	17.7	DNC
Souza 2 Model	62.5	DNC	DNC	74.2	25	33.3	27.3	DNC
Souza2 Model, No 500mb Temperature	62.5	DNC	DNC	80.6	0	DNC	23.1	DNC

Table 2.13. Freezing Precipitation otherwise same as Table 2.11.

Model Name	PIEDMONT	COAST
Traditional Model	0	0
Traditional Plus Model	48.8	0
Keeter Model	68.3	DNC
Souza1 Model	79.5	DNC
Souza1 Model, NO 500mb Temperature	69.2	DNC
Souza 2 Model	76.9	DNC
Souza2 Model, No 500mb Temperature	71.8	DNC

Table 2.14. Freezing Precipitation, Regional approach. Same as Table 2.12

Tables 2.13 and 2.14 show that the inclusion of low level thickness information or low- to mid-level temperatures significantly improve the ability of the model to detect freezing precipitation. Areas affected by cold air damming had virtually the same percentage of freezing precipitation cases as frozen precipitation cases. As expected, the sensitivity of the freezing precipitation equations is significantly lower than that of frozen precipitation. Probabilities of detection and Schwartz criterion showed significant improvement when variables representing the low-mid level nature of freezing precipitation were included.

Freezing precipitation is rare along the coast in the southeastern United States. The very few cases of freezing precipitation during the research data period did not provide the model enough information to converge and produce a quality forecast.

2.5 Experimental Design: Nomogram

The regression portion of TOP DOG only allows for the differentiation of liquid from freezing precipitation and of liquid from frozen precipitation. As stated previously, the ability to differentiate amongst various mixed precipitation types is very important to today's forecaster. TOP DOG's nomograms are designed to graphically discriminate amongst these mixed precipitation types and to characterize the precipitation event and determine where to place forecast emphasis.

Two styles of precipitation type nomograms were developed. Both nomograms may provide the forecaster with a general physical representation of or suggest a physical link to the atmospheric processes found to be critical in the

determination of precipitation type The nomograms include the two most important variables (in terms of chi-square score and significance tests) for the prediction of freezing precipitation and frozen precipitation as determined from the development of regression equations. The X-axis contains the values of thickness (or other atmospheric variable) at the lower level of the atmosphere while the Y-axis is the value of thickness (or other atmospheric variable) of the higher level (typically the mid-level). The type of precipitation or precipitation subtype is plotted versus both X and Y values. The forecaster finds the X,Y values and finds their intersection. He/she then reads the precipitin type associated with these values

The first nomogram style is designed to supplement or replace the regression equations and should be used to differentiate amongst the major precipitation type categories (i.e. liquid, frozen, or freezing {See Table 2.2 for definitions}). This style of nomogram provides the forecaster with an overall view of the precipitation type expected during the period. The second style of nomogram provides the forecaster with the ability to differentiate amongst various precipitation subtypes and to best characterize the precipitation event to the public. (See Table 2.3).

Figure 2.3 shows an example of the first nomogram style for the Traditional Plus model for Greensboro, NC. Assume that the 1000-700mb thickness is 2860m and the 700-500mb thickness is 2550m. Reading the intersection of these values on the nomogram would lead to a forecast of liquid precipitation. Applying the same thickness values to precipitation subtype nomogram (See Figure 2.4), would lead to a forecast of rain mixed with snow with little or no accumulation of frozen

precipitation. The second nomogram style allows the forecaster to be much more specific in forecast wording.

The nomograms also allow for some physical interpretation of the important physical processes involved in precipitation type forecasting. For example, a forecaster can see if the airmass is very cold in the lower levels (as indicated by lower thickness values) and relatively warm in the mid-upper levels (higher thickness values). This situation would show a cold air damming situation with warm air overrunning the cold air dome.

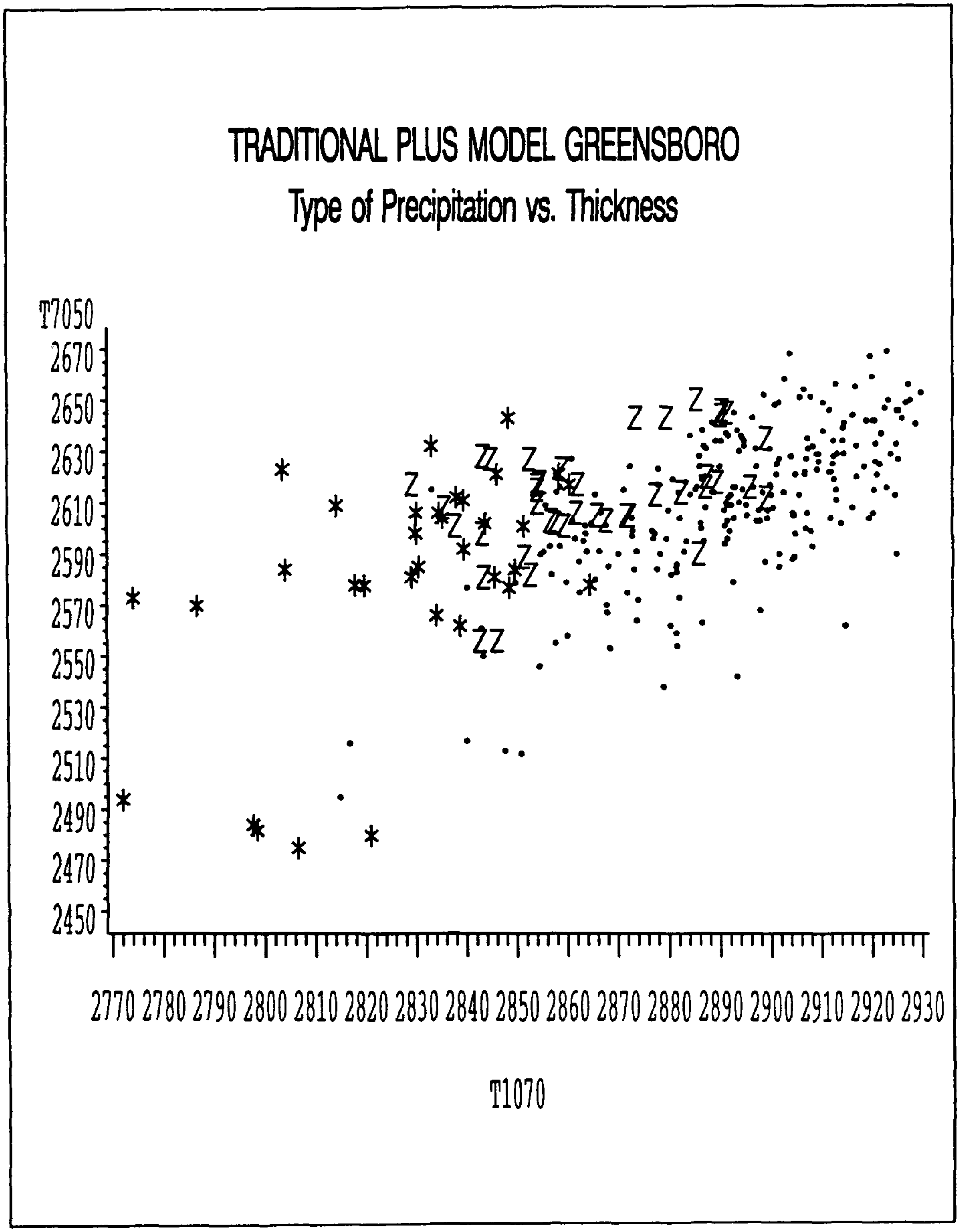

Figure 2.3. Nomogram of main precipitation type based on the Traditional Plus model for Greensboro, NC. T1070 along the X-axis is the 1000-700mb thickness in meters. T7050 along the Y-axis is the 700-500mb thickness in meters. Type is plotted as follows: * indicates frozen precipitation; Z indicates freezing precipitation; and • indicates liquid precipitation.

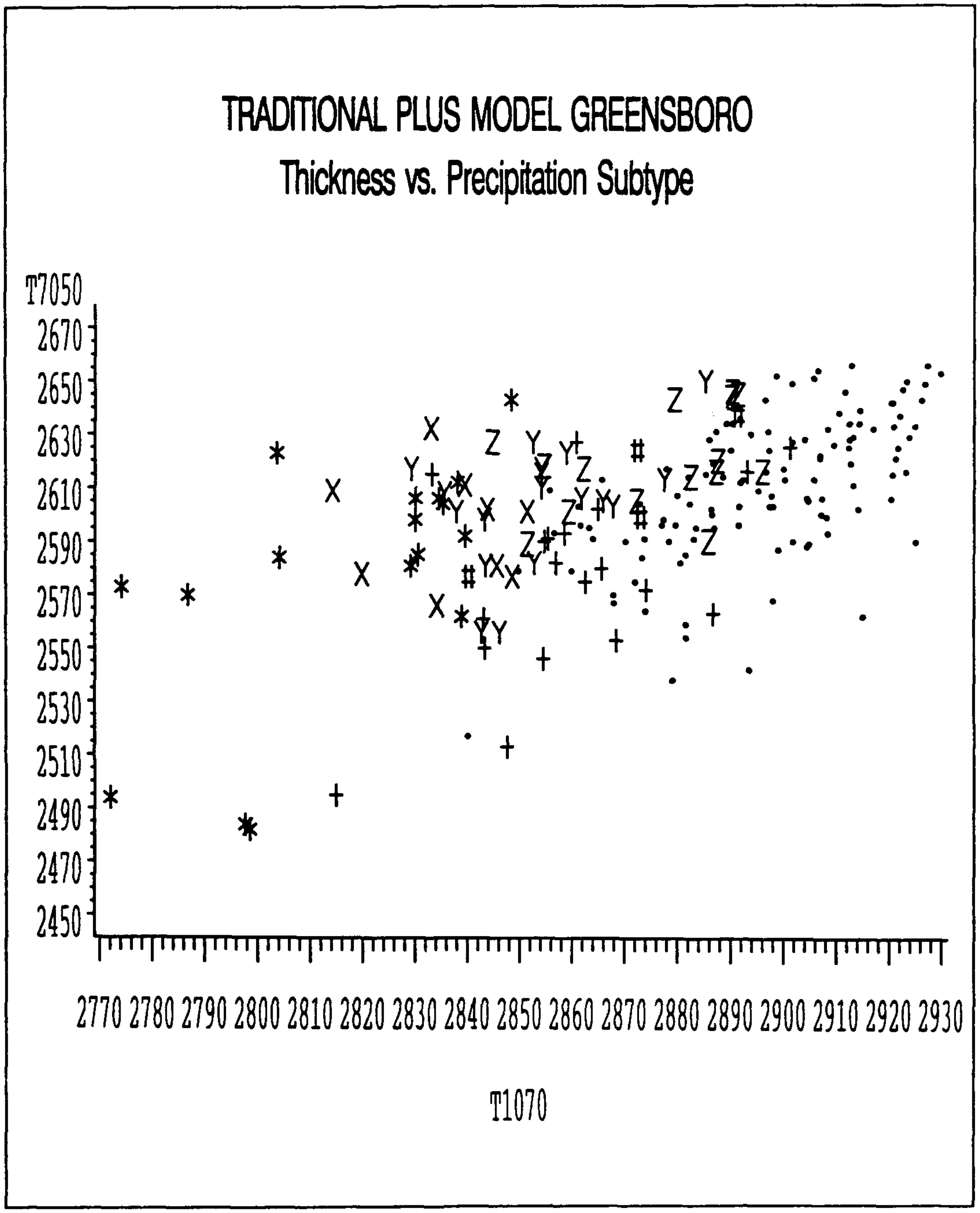

Figure 2.4. Nomogram of precipitation subtype based on the Traditional Plus model for Greensboro, NC. T1070 along the X-axis is the 1000-700mb thickness in meters. T7050 along the Y-axis is the 700-500mb thickness in meters. Type is plotted as follows: * indicates all snow; X indicates mixed frozen precipitation; Δ indicates all sleet; Z indicates freezing precipitation; Y indicates freezing rain with mixed frozen; # indicates rain mixed with freezing rain; + indicates mixed liquid; and • indicates liquid precipitation.

3 TOP DOG Examined

3.1 Overview

TOP DOG is a significant improvement to currently available forecasting techniques. Complete TOP DOG output and analysis, including regression diagnostics, model accuracy, regression equations and nomograms are provided for the single station Greensboro, NC (GSO) to assist the forecaster's understanding of the technique. A summary of the output is provided for the SEUS' Piedmont region (PIEDMONT) to illustrate the use of TOP DOG on a regional basis.

3.2 Greensboro, NC

3.2.1 Regression Portion

The Schwartz Criterion (SC) provides a simple but powerful measure to compare the relative efficacy of the proposed explanatory regression models (SAS, 1990). The traditional model is a very poor model for forecasting freezing and frozen precipitation and is not included in the overview graphs of model efficacy. Figure 3.1 illustrates the efficacy of all the proposed models for the prediction of frozen precipitation. The figure shows that the Souza1 model is the most desirable proposed model. However, the SC scores are comparable amongst the Keeter and Souza (1 and 2) models. All proposed models, except for the Traditional, are comparable in efficacy. The Souza2 (Eq 3.1A) model is the best model for frozen precipitation overall based on model sensitivity (See 3.2.1.5) while the Souza1 model has a slightly lower false positive rate (See 3.2.1.4) and value of the Schwartz

Criterion. Figure 3.2 shows the same information as Figure 3.1 except for freezing precipitation. The relative efficacy for the models for freezing precipitation is much clearer. All models proposed except for the Traditional and Traditional Plus are comparable in efficacy. The Souza1 or Souza2 models (versions including the temperature at 950mb) are superior to the other proposed models. Interestingly, after forward selection both regression equations based on these models (i.e. versions including temperature at 950mb) are identical and after forward selection include only temperature at 950mb.

After forward selection on the proposed models, the top model for forecasting frozen precipitation for Greensboro, NC is the Souza1 (Eq. 3.1A) model (same regression equation with/without temperature at 500mb). The best freezing precipitation regression model for GSO is either the Souza1 or Souza2 models (temperature at 950mb included). These regression equations provide the conditional probability (p) of freezing or frozen precipitation forecasts. The precipitation type regression equations are:

FROZEN: $\text{Logit}(p) = 353.5 + (-0.3992)\text{T9585}$ **(3.1A)**

FREEZING: $\text{Logit}(p) = -2.5061 + (-1.1652)\ \text{Temp950}$ **(3.2)**

where T is the thickness (in meters) between two levels in the atmosphere. The thickness of the 950-850mb layer (T9585) is a measure of the mixing or transition layer between the cold air dammed below 950mb and the warmer air overrunning the cold air through about the 850mb level. Temp950 (degrees Celsius) is the

temperature at 950mb and provides an indicator of the relative strength of the cold air dammed against the Appalachian mountains.

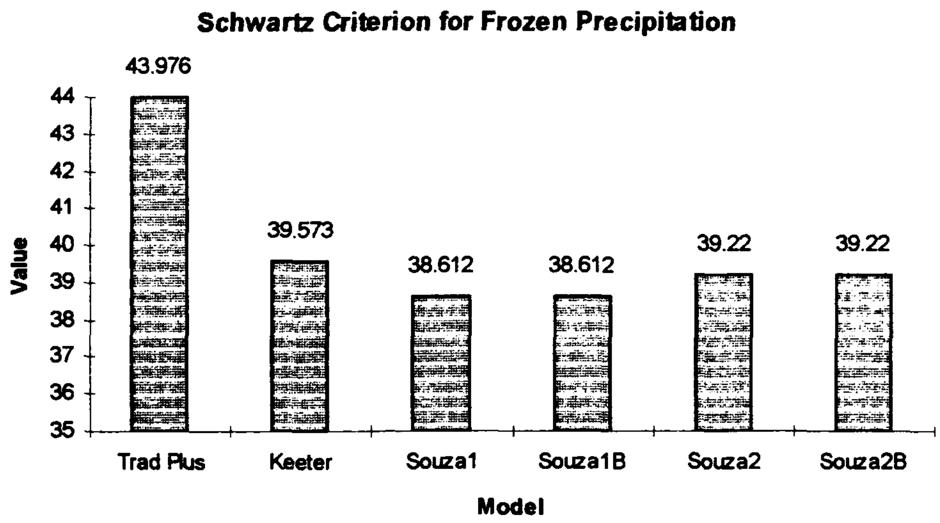

Figure 3.1. Schwartz Criterion for the Derived Regression Model for Differentiation of Frozen Precipitation from Liquid Precipitation. The letter B after a model indicates that the temperature variable was not included in the model. Lower values of the Schwartz Criterion indicate a better fitting model.

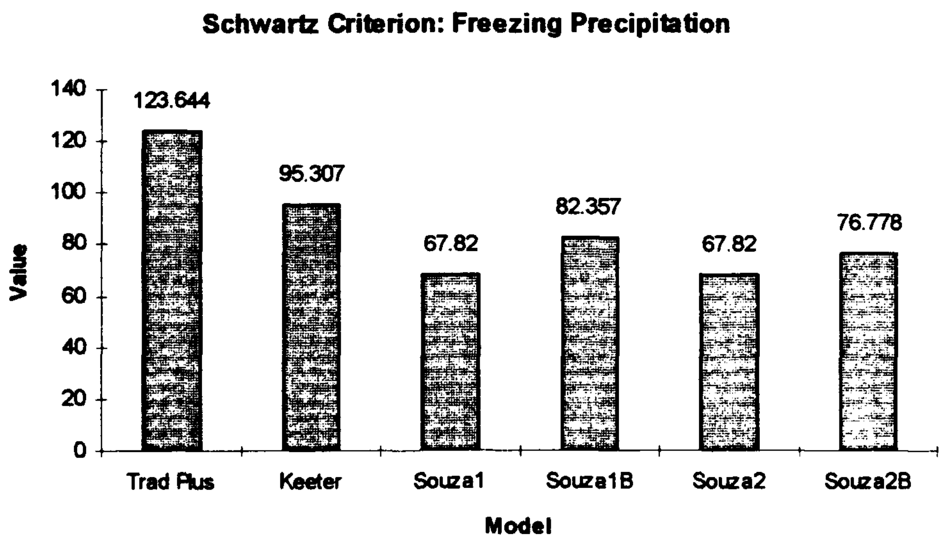

Figure 3.2. Same as Figure 3.1 but for Freezing Precipitation.

3.2.1.1 The Traditional Model

The regression equations for the prediction of frozen (3.3) and freezing (3.4) precipitation based on the traditional model are:

FROZEN: $\text{Logit}(p) = 175.6 + (-0.0325)T1050$ **(3.3)**

FREEZING: $\text{Logit}(p) = 62.3202 + (-0.0116)T1050$ **(3.4)**

where T1050 is the 1000-500mb thickness and p is the conditional probability of frozen or freezing precipitation.

This research supports the school of thought that the 1000-500mb thickness is not a representative measure for forecasting precipitation type. Figure 3.3 shows that the Traditional model has a very poor ability to forecast frozen precipitation for GSO (based on sensitivity). Figure 3.4 shows that the model indicates no ability (probability of detection or sensitivity is zero) to forecast freezing precipitation. Equation 3.3 shows that the 50% conditional probability for frozen precipitation is achieved with a 1000-500mb thickness of 5570 meters compared to the traditional 5400m demarcation. This high thickness value found for the 50% conditional probability is much higher than would be expected. This result further illustrates the difficulty in applying this model operationally. Clearly, the 1000-500mb thickness is too crude a measure to properly account for the low level nature of cold air damming and its effect on precipitation type at Greensboro, NC.

Operationally, this traditional method is currently out of favor as a forecast tool in the SEUS. TOP DOG confirms the conventional wisdom that forecasters must look at partial thicknesses as they forecast precipitation type in this region.

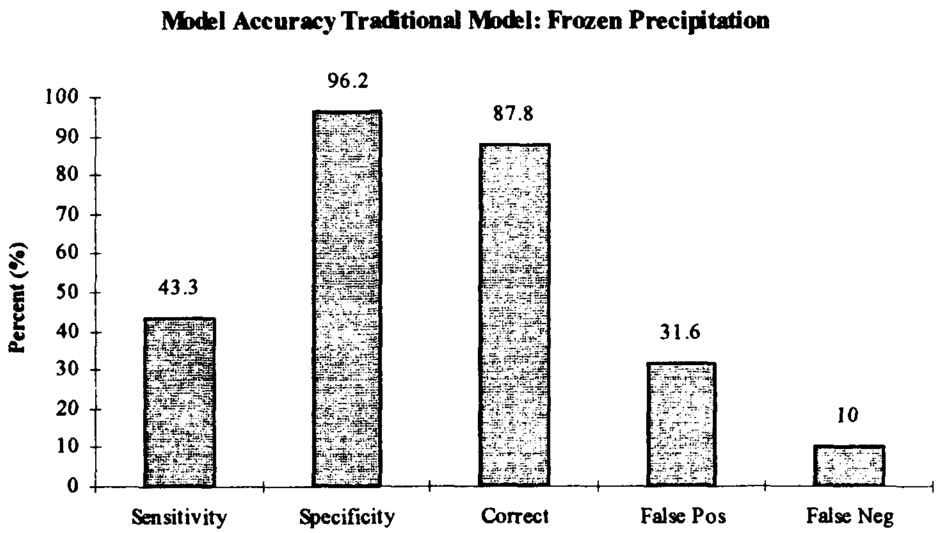

Figure 3.3 Model Accuracy, Frozen Precipitation, for the Traditional Model. Sensitivity (POD) is defined as the proportion of frozen or freezing cases predicted to be frozen or freezing. Specificity is the proportion of liquid cases predicted to be liquid. The false positive rate (FPR or False Pos), known operationally as the false alarm rate/ratio (FAR) is the proportion of predicted frozen or freezing cases that were observed as liquid cases. The false negative rate (FNR or False Neg), known operationally as the bias (BIAS), is the proportion of predicted no cases that are observed as cases. Overall correct is the percentage of all cases correctly categorized by the model. POD, FAR/FPR, and FNR/Bias are defined in §2.4.4.

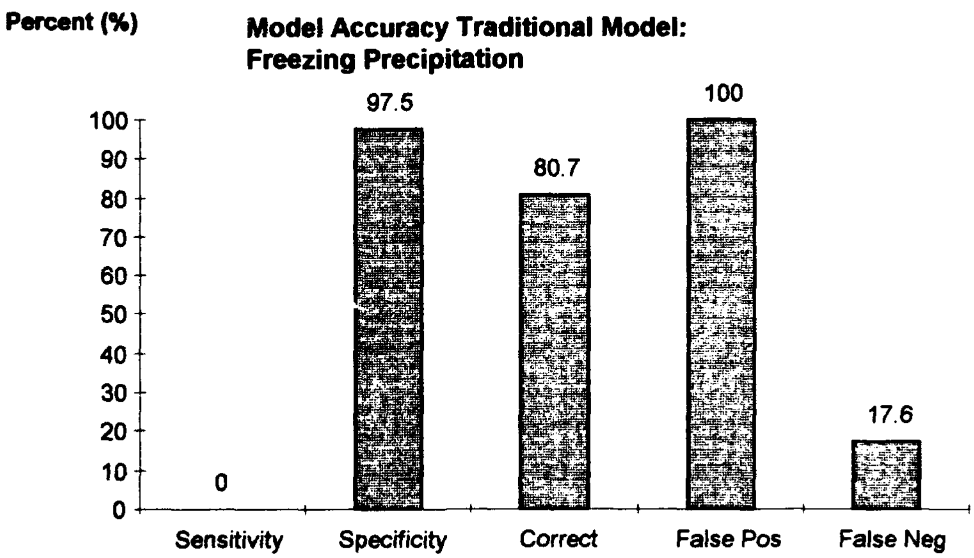

Figure 3.4. Same as Figure 3.3 except for Freezing Precipitation.

3.2.1.2 Traditional Plus Model

The regression equations for the prediction of frozen (3.5) and freezing (3.6) precipitation based on the Traditional Plus model are:

$$\text{FROZEN:} \quad \text{Logit}(p) = 462.2 + (-0.2059)T1070 + (0.0617)T7050 \qquad \textbf{(3.5)}$$

$$\text{FREEZING:} \quad \text{Logit}(p) = 132.4 + (-0.0996)T1070 + (0.0585)T7050 \qquad \textbf{(3.6)}$$

where T1070 is the 1000-700mb thickness, T7050 is the 700-500mb partial thickness, and p is the conditional probability of frozen or freezing precipitation.

The Traditional Plus model is a significant improvement as a forecast model, for both frozen and freezing precipitation, from the Traditional model. Figure 3.5 shows that the probability of detection (POD, a.k.a. Sensitivity) of frozen precipitation doubles when the 1000-500mb thickness (see figure 3.3) is subdivided into 1000-700 and 700-500mb partial thicknesses. The Traditional Plus model provides some forecast skill for freezing precipitation (See Figure 3.6). The 1000-700mb thickness represents the layer through which snow falls and either changes form or remains as snow. This level measures the relative strength of the low-mid level cold air. The 700-500mb thickness provides a measure of the thermal properties of the layer in which snow forms and begins its descent.

This research confirms the findings of Keeter and Cline (1991). The 1000-700mb thickness and 700-500mb thickness are sufficient to distinguish snow from rain events. (i.e. frozen versus liquid in TOP DOG).

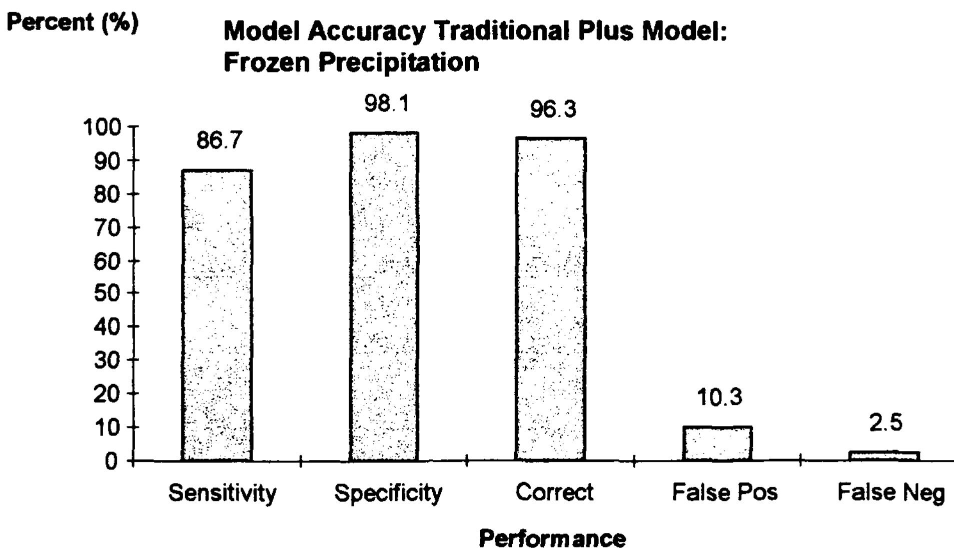

Figure 3.5 Model Accuracy, Frozen Precipitation, for the Traditional Plus Model. Sensitivity, specificity, overall correct, false positive rate and false negative rates in percent as defined in Figure 3.3.

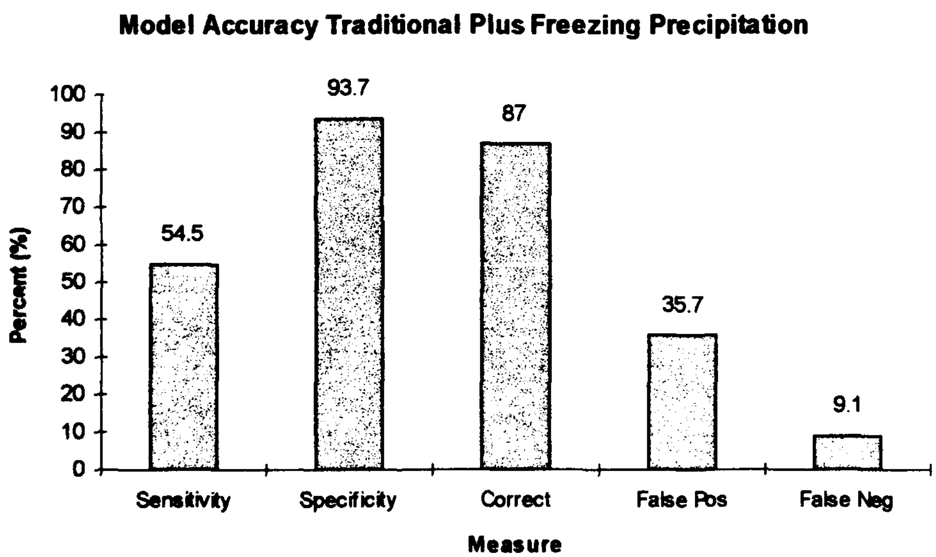

Figure 3.6. Same as Figure 3.4 except for Freezing Precipitation.

3.2.1.3 Keeter Model

The regression equations for the prediction of frozen (3.6) and freezing (3.7) precipitation based on the Keeter model are:

$$\text{FROZEN:} \quad \text{Logit}(p) = 358.3 + (-0.2759)T1085 \tag{3.6}$$

$$\text{FREEZING:} \quad \text{Logit}(p) = 245.3 + (-0.1880)T1085 \tag{3.7}$$

where T1085 is the 1000-850mb thickness and p is the conditional probability of frozen or freezing precipitation.

The Keeter model while providing only a slight improvement in the forecasting ability for frozen precipitation, provides a significant improvement for over the Traditional Plus model for the forecasting of freezing precipitation. (See Figures 3.7 and 3.8 and compare to figures 3.5 and 3.6). These results confirm that Keeter and Cline's (1991) subdivision of the 1000-700mb thickness into partial thicknesses (i.e. 1000-850 and 850-700mb thicknesses) can be used to differentiate freezing rain events from liquid and frozen events. TOP DOG indicates that the processes most affecting precipitation type occur below the 850mb level (approximately 5000 feet). This layer is the layer of strongest thermal advection, both cold and warm. While the Keeter model shows improved skill, the 1000-850mb thickness layer is too crude to differentiate the cold advection in the lowest layers (cold air damming region as defined by Bell and Bosart (1988)) and overrunning warm air advection in the mid layers.

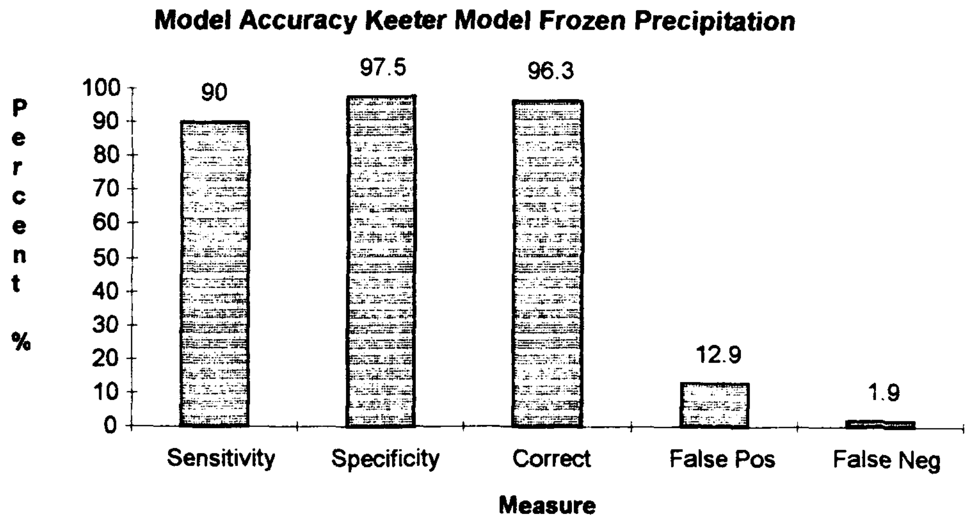

Figure 3.7. Model Accuracy, Frozen Precipitation, for the Keeter Model. Sensitivity, specificity, overall correct, false positive rate and false negative rates in percent as defined in Figure 3.3.

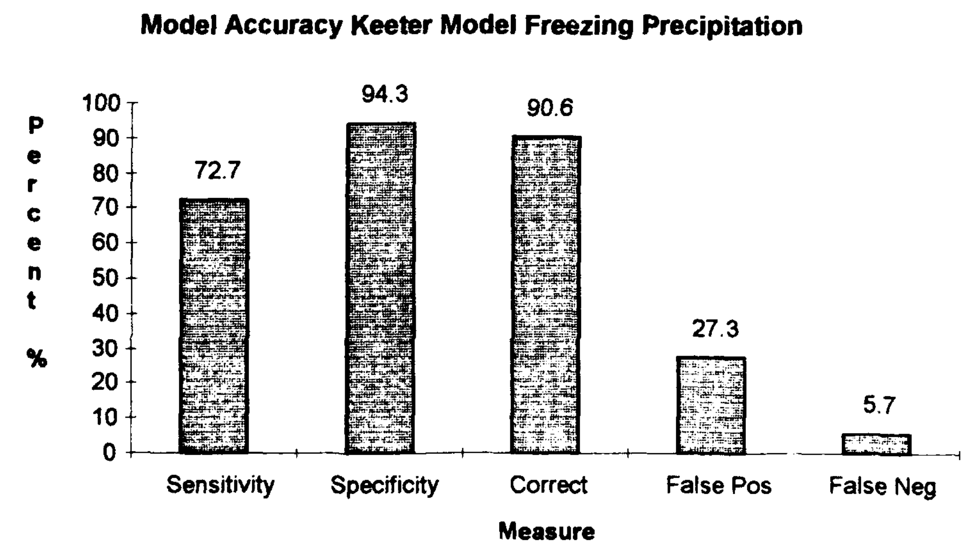

Figure 3.8. Same as Figure 3.5 except for Freezing Precipitation.

3.2.1.4 Souza1 Model

The regression equations for the prediction of frozen (3.8) and freezing (3.9/3.10) precipitation based on the Souza1 model are:

FROZEN: Logit (p) = 353.5 + (-0.3992)T9585 **(3.8)**

FREEZING:

Souza1A (with 950mb temperature): Logit (p) = -2.5061 +(-1.1652)Temp950 **(3.9)**

Souza1B (NO 950mb temperature): Logit (p) = 296.5 + (-0.5016)T1095 + (-0.1007)T9585 **(3.10)**

where Temp950 is the temperature at 950mb, T1095 is the 1000-950mb thickness, T9585 is the 950-850mb thickness, and p is the conditional probability of frozen or freezing precipitation.

The Souza1 model shows a slight improvement in the forecasting of frozen precipitation and a larger improvement (in all measures) for the forecasting of freezing precipitation in both of its forms (with/without temperature at 950mb) compared to the Keeter Model. (Compare Figures 3.7 and 3.9 for frozen precipitation and figures 3.8 and 3.10 for freezing precipitation).

Bell and Bosart (1988) defined the top of cold air damming at between 950 and 930mb and they noted the existence of a warm overrunning layer (approximately 850mb up through 700mb) and mixing or transition layer (about 950/930mb to 850mb) between the two. The Souza1 model was designed to improve on the Keeter model by measuring the strength (depth and relative

coldness) of cold air damming (1000-950 thickness), the mid level warm air overrunning (advection) (850-700 thickness) while concurrently measuring the mixing transition layer (950-850mb thickness). The transition layer includes the inversion at the top of the cold air dome and the level of strongest warm advection overrunning the cold air. The temperature at 950mb is a measure of the strength of cold air damming. The colder and deeper the dammed air, the lower the 950mb temperature. TOP DOG's results support the hypotheses of Stewart (1987, 1992) and Stewart et al (1990) that the lowest levels of the atmosphere are the most critical to forecasting precipitation type. The Souza2 model also provides the forecaster with a tool to quantify the relative strengths of cold air damming and the accompanying overrunning and the rate of decay of the cold air damming. The mixing layer (950-850mb) is crucial to understanding frozen versus liquid precipitation. The cold air damming region (as quantified by the 1000-950mb thickness) allows the forecaster to differentiate amongst frozen versus freezing more accurately.

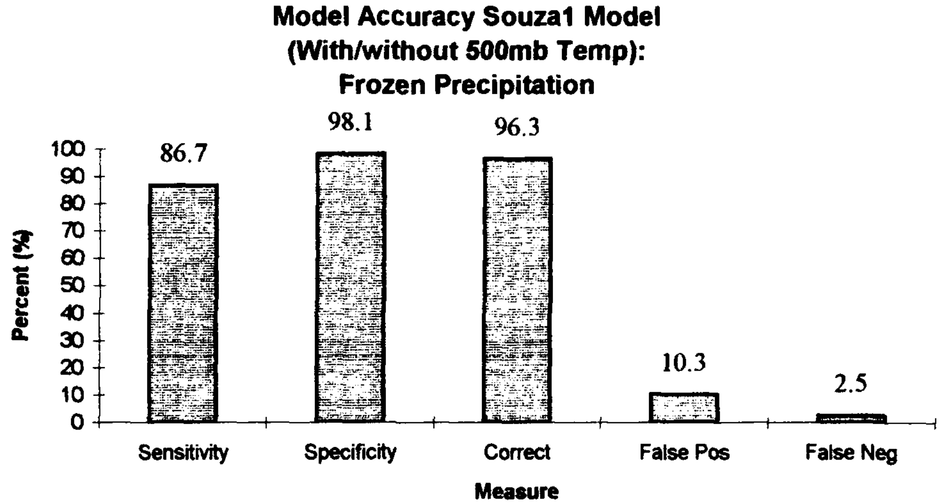

Figure 3.9. Model Accuracy, Frozen Precipitation, for the Souza1 Model with/without temperature at 500mb. Sensitivity, specificity, overall correct, false positive rate and false negative rates in percent as defined in Figure 3.3.

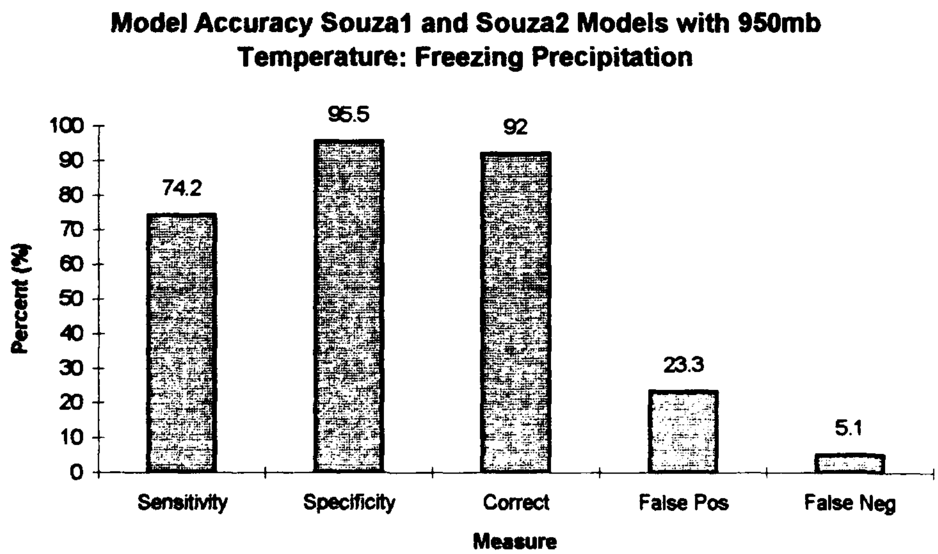

Figure 3.10. Model Accuracy, Freezing Precipitation, for the Souza1 and Souza2 Models with temperature at 950mb. Sensitivity, specificity, overall correct, false positive rate and false negative rates in percent as defined in Figure 3.3.

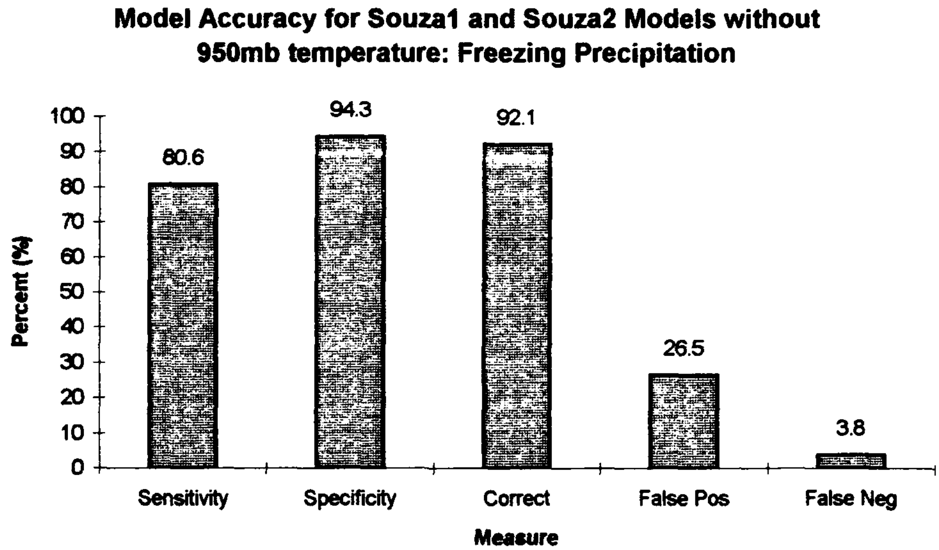

Figure 3.11. Model Accuracy, Freezing Precipitation, for the Souza1 and Souza2 Models without temperature at 950mb. Sensitivity, specificity, overall correct, false positive rate and false negative rates in percent as defined in Figure 3.3.

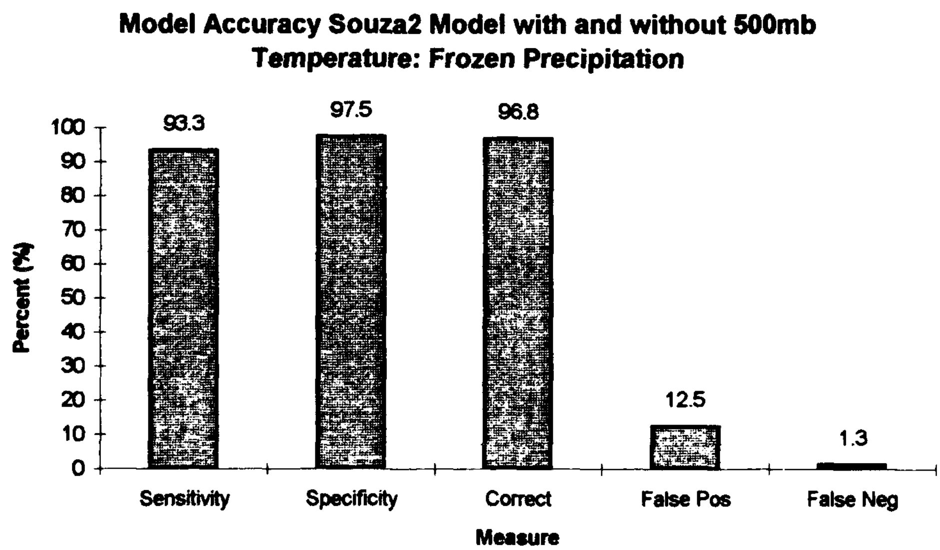

Figure 3.12. Model Accuracy, Frozen Precipitation, for the Souza2 Model with/without temperature at 500mb. Sensitivity, specificity, overall correct, false positive rate and false negative rates in percent as defined in Figure 3.3.

3.2.1.5 Souza2 Model

The regression equations for the prediction of frozen (3.11) and freezing (3.12/3.13) precipitation based on the Souza2 model are:

FROZEN: $\text{Logit}(p) = 478.4 + (-0.3895)T1090 + (-0.0973)T8570$ **(3.11)**

FREEZING:

Souza2 (with 950mb temperature): $\text{Logit}(p) = -2.5061 + (-1.1652)\text{temp}950$ **(3.12)**

Souza2B (NO 950mb temperature): $\text{Logit}(p) = 279.8 + (-0.3316)T1090$ **(3.13)**

where temp950 is the temperature at 950mb, T1090 is the 1000-900mb thickness, T8570 is the 850-700mb thickness, and p is the conditional probability of frozen or freezing precipitation.

The Souza2 model showed slight improvement (sensitivity) over the Souza1 model in the forecasting of frozen precipitation (compare figures 3.9 and 3.12), but no difference (with/without 950mb temperature) in the forecasting of freezing precipitation. (See figures 3.10 and 3.11).

The Souza2 model is an offshoot of the Souza1 model. Its intent is to take into account the potential that the cold air damming layer is deeper (closer to 930mb than 950mb) than shown by Bell and Bosart (1988) especially close to the mountains. Since radiosonde data is routinely available at 50mb intervals up through about 500mb, and since the 925 mb level only recently became a mandatory level for radiosonde operations, the 900mb level was the next highest routinely available level.

3.2.2 Nomogram Portion

3.2.2.1 Overview

Three styles of precipitation type nomograms were developed for GSO. All provide the forecaster with a window on the atmospheric processes found to be critical in the determination of precipitation type as described in analysis for each model found in section 3.2.1. TOP DOG's nomograms are climatological. They help provide a clue to help in the detection of relatively infrequent events such as ice pellets or freezing rain.

The nomograms include the two most important variables (in terms of chi-square score and significance tests) for the prediction of freezing precipitation and frozen precipitation as determined from the development of regression equations. The X-axis contains the values of thickness (or other atmospheric variable) at the lower level of the atmosphere while the Y-axis is the value of thickness (or other atmospheric variable) of the higher level (typically the mid-level). The type of precipitation or precipitation subtype is plotted (actual cases for styles 1 and 2, schematic for style 3) versus both X and Y values. The forecaster finds the X,Y values and finds their intersection. He/she then reads the precipitation type associated with these values

The first nomogram style is designed to differentiate amongst overall precipitation type (i.e. liquid, frozen, or freezing {See Table 2.2 for definitions}). This style of nomogram provides the forecaster with an overall view of the

precipitation type expected during the period. The second style of nomogram provides the forecaster with the ability to differentiate amongst various precipitation subtypes. The third style is a schematic representation of the precipitation type forecast models. The schematic is hand drawn based on a combination of the regional precipitation subtype and single station precipitation subtype nomograms.

The Traditional and Traditional Plus models both are insufficient for the forecasting of freezing precipitation. The first two nomogram styles for the Traditional Plus model was used in Chapter 2 (Section 2.7.2: Figures 2.3 and 2.4) to illustrate the concept of nomograms.

Forecasters should use these nomograms as a supplement to current forecast techniques such as the NGM MOS. A thorough understanding of the synoptic situation and the local and mesoscale effects is critical to proper use of these nomograms operationally. TOP DOG and its associated nomograms were designed and function best under cold air damming situations.

3.2.2.2 Keeter Model

The nomograms for the Keeter model use the 1000-850mb thickness (T1085) and the 850-700mb (T8570) thickness for the forecasting of precipitation type. While the 850-700mb thickness does not appear in the regression equations for either frozen or freezing precipitation, it is the next most significant variable in the model for both of these types.

The 1000-850mb thickness is a measure of the low-mid levels while the 850-700mb thickness measures warm air overrunning the cold air. Figure 3.13 is the schematic of precipitation type. Figure 3.14 is the overall precipitation type nomogram and figure 3.15 is the precipitation subtype nomogram.

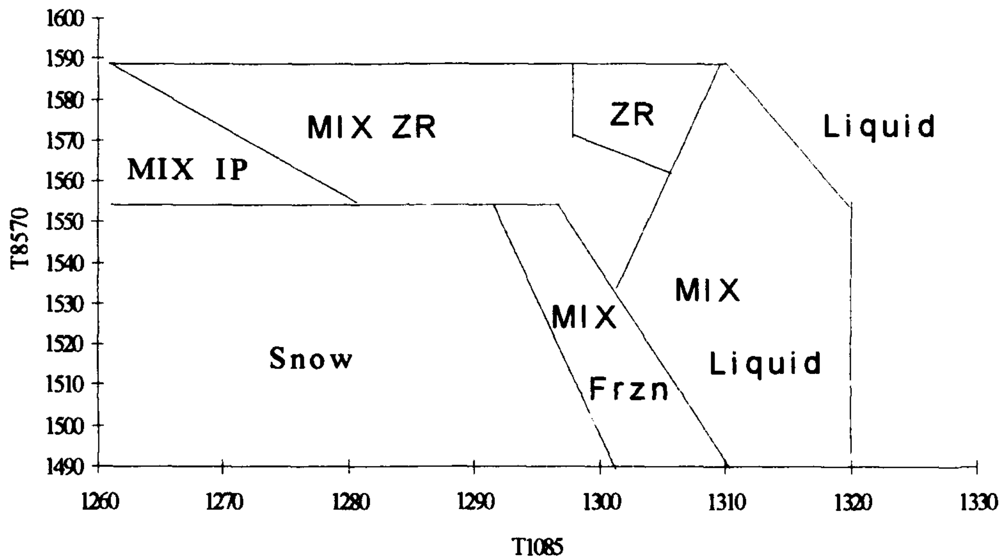

Figure 3.13 Schematic Nomogram of Precipitation Type derived from the Keeter Model. T1085 is the 1000-850 mb thickness. T8570 is the 850-700mb thickness. Snow indicates area of all snow. Mix IP is the area where a mixed frozen event is expected but ice pellets should be dominant type. Mix ZR: freezing rain mixed with frozen precipitation but little or no accumulation of frozen precipitation. ZR: All Freezing Rain. Mix Frzn: Frozen (i.e. snow/ice pellets) accumulation but may be mixed with freezing rain or rain. Mix Liquid: Rain mixed with nonaccumulating frozen precipitation. Liquid: All rain.

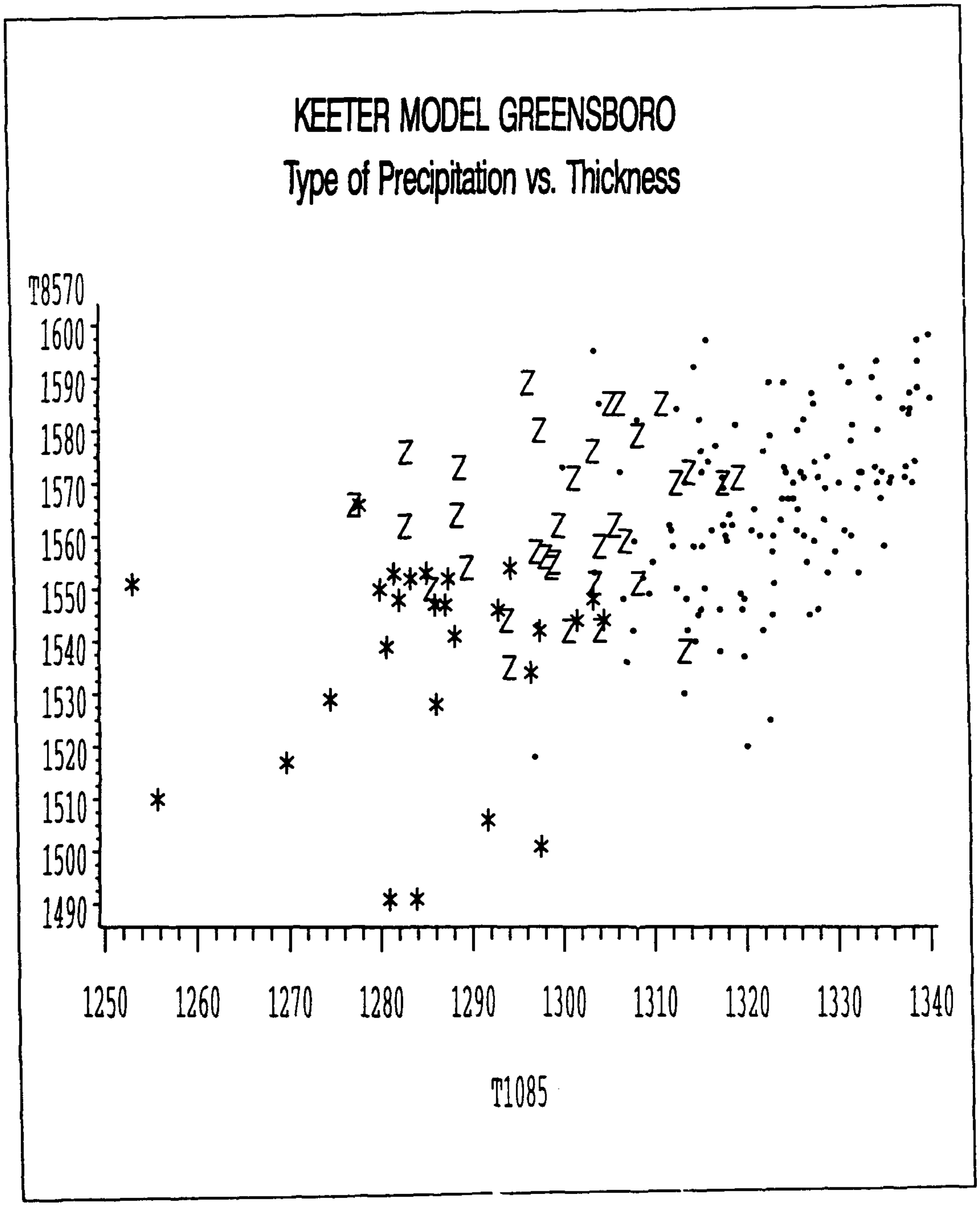

Figure 3.14. Nomogram of main precipitation type based on the Keeter model for Greensboro, NC. T1085 along the X-axis is the 1000-850mb thickness in meters. T8570 along the Y-axis is the 850-700mb thickness in meters. Type is plotted as follows: * indicates frozen precipitation; Z indicates freezing precipitation; and • indicates liquid precipitation.

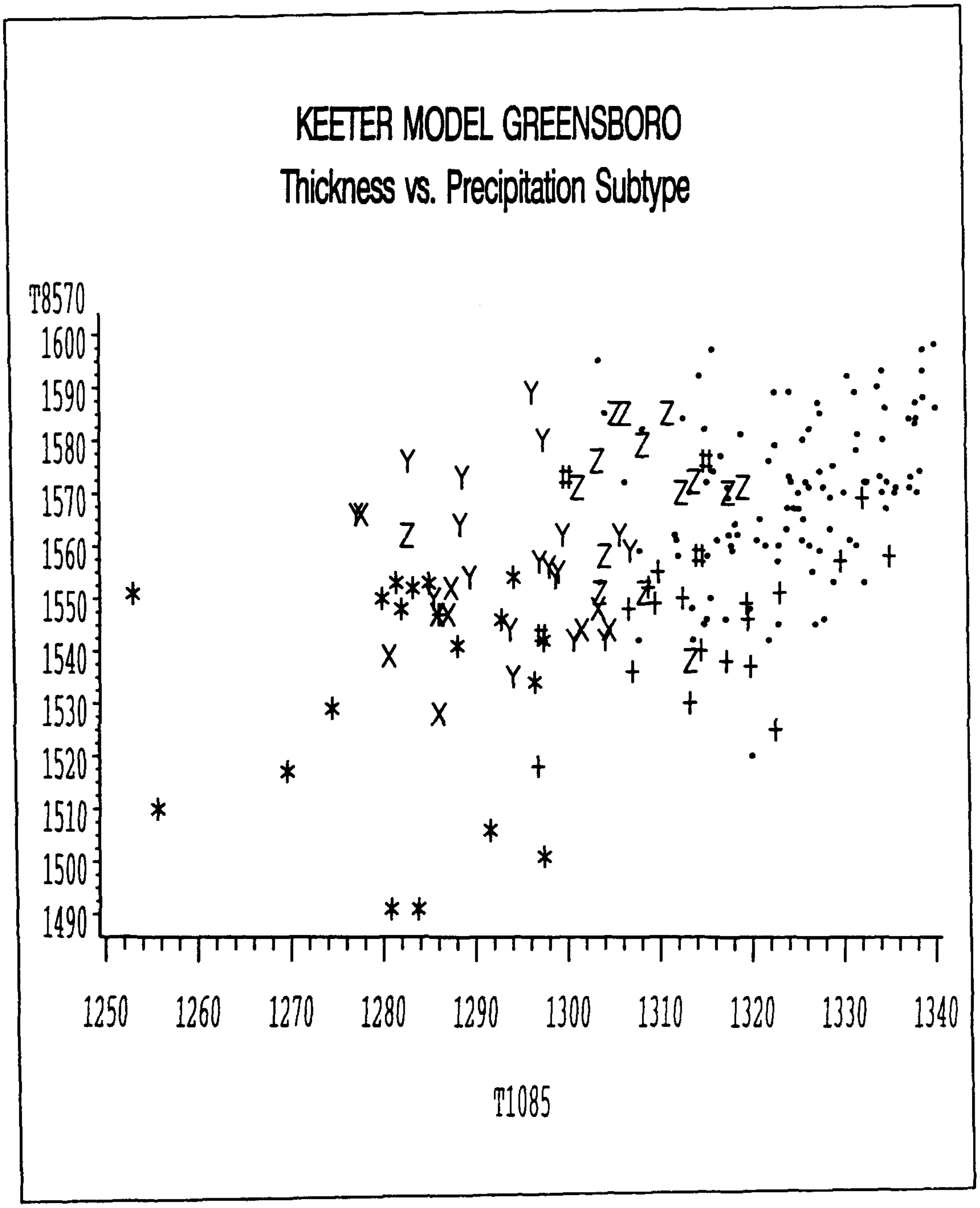

Figure 3.15. Nomogram of precipitation subtype based on the Keeter model for Greensboro, NC. T1085 along the X-axis is the 1000-850mb thickness in meters. T8570 along the Y-axis is the 850-700mb thickness in meters. Subtype is plotted as follows: * indicates all snow; X indicates mixed frozen precipitation; Δ indicates all sleet; Z indicates freezing precipitation; Y indicates freezing rain with mixed frozen; # indicates rain mixed with freezing rain; + indicates mixed liquid; and • indicates liquid precipitation.

3.2.2.3 Souza1 Model

The nomograms for the Souza1 model use the 1000-950mb thickness (T1095) and the 950-850mb (T9585) thickness for the forecasting of precipitation type. While T1095 does not appear in the equation for frozen precipitation it is the next most significant variable in the model. Temperature 950mb showed relatively little skill in forecasting frozen precipitation so it was not included in the nomograms. The 1000-950mb thickness is a measure of the low level under the influence of cold air damming while the 950-850mb thickness measures the mixing layer between the cold air and the warm air overrunning the cold air. Figure 3.16 is the schematic of precipitation type. Figure 3.17 is the overall precipitation type nomogram and Fig. 3.18 is the precipitation subtype nomogram.

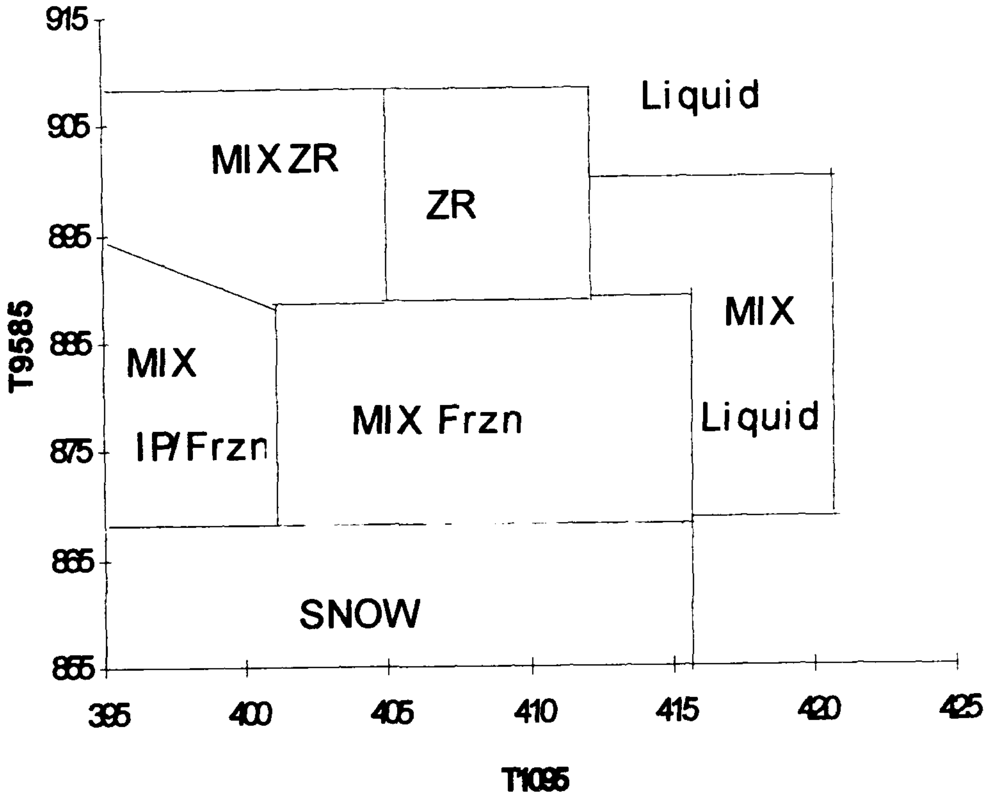

Figure 3.17. Same as figure 3.13 except for the Souzal Model. T1095 is the 1000-950mb thickness. T9585 is the 950-850 mb thickness.

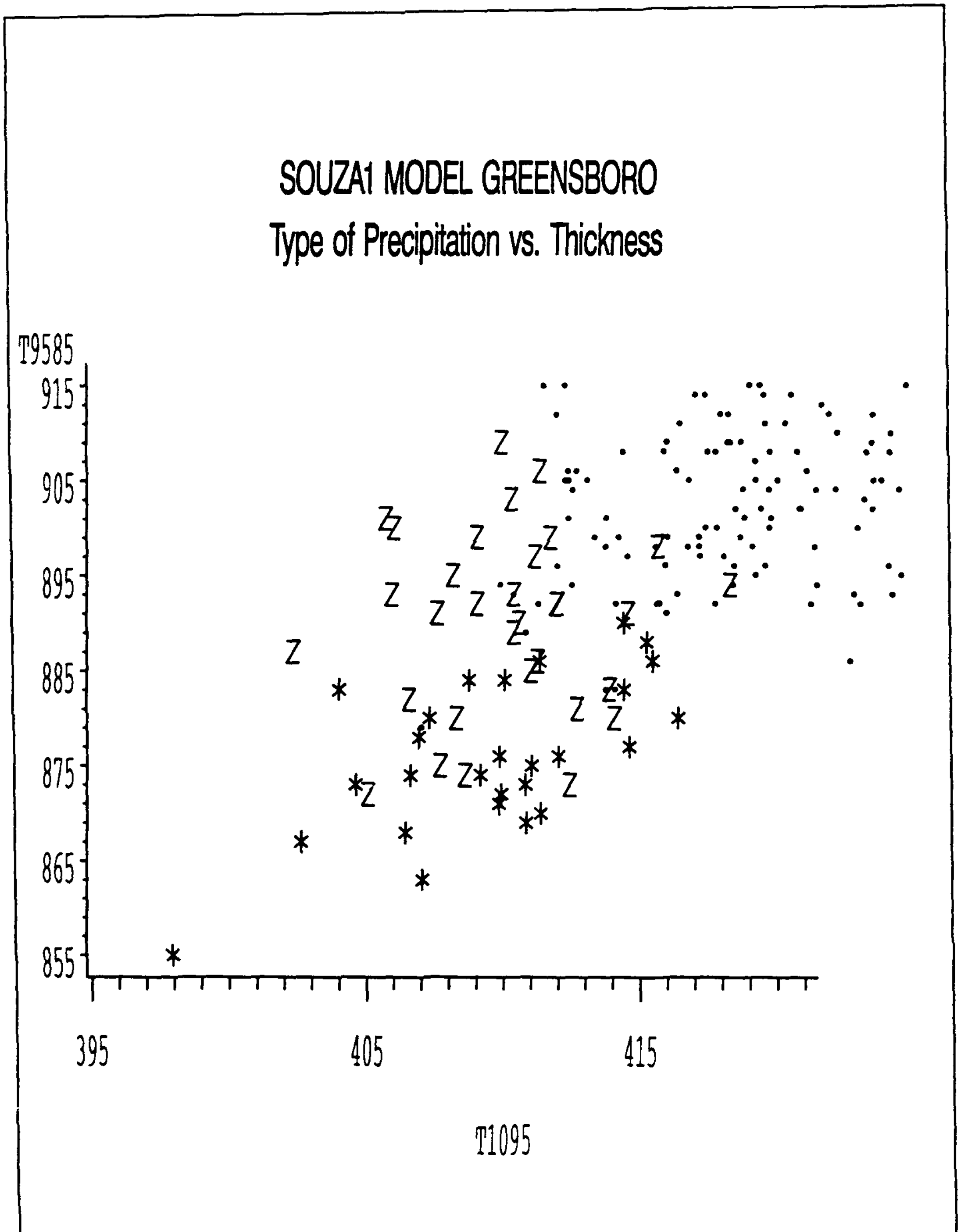

Figure 3.18. Same as figure 3.14 except for Souza1 Model. T1095 is the 1000-950mb thickness. T9585 is the 950-850 mb thickness.

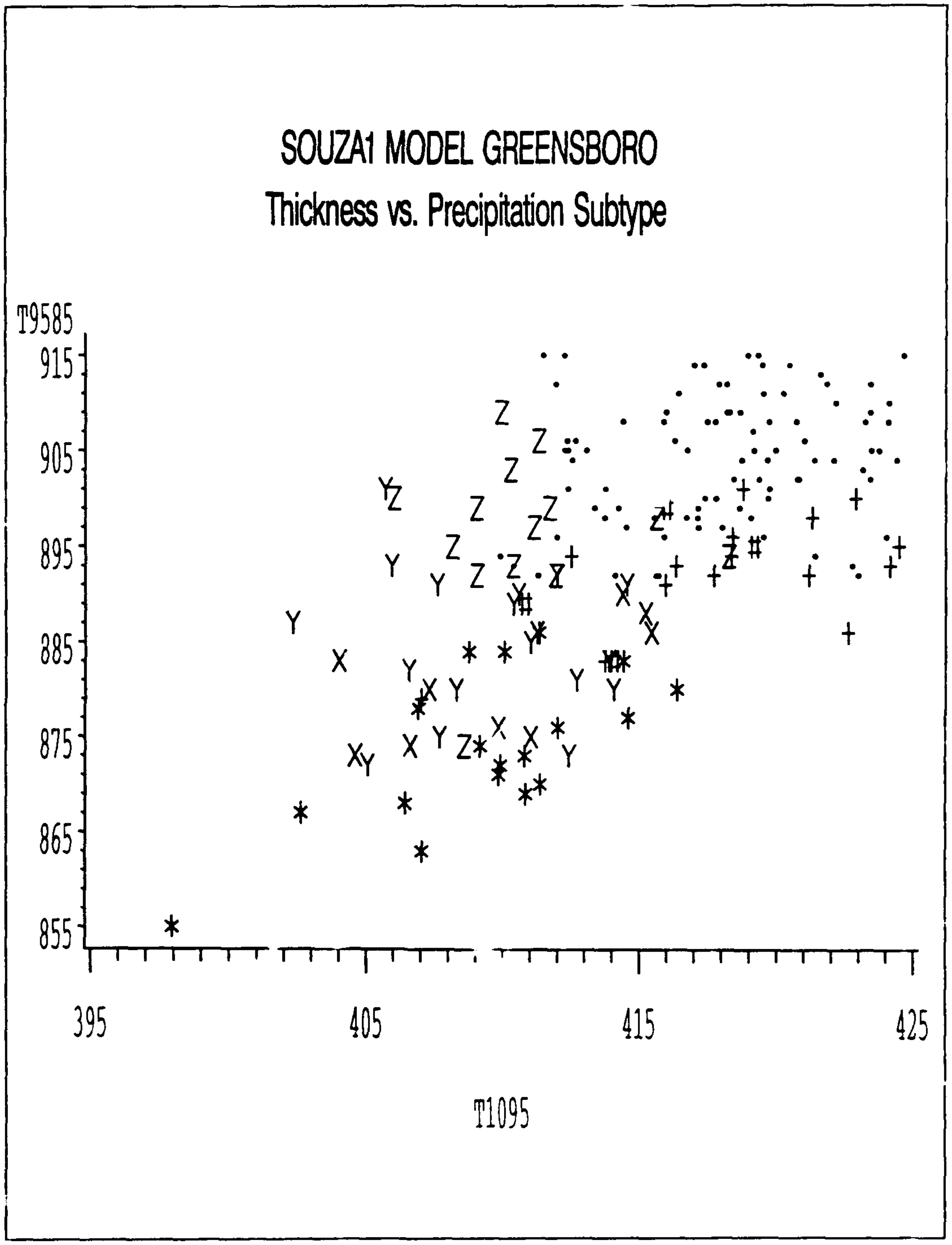

Figure 3.19. Same as figure 3.15 except for Souza1 Model. T1095 is the 1000-950mb thickness. T9585 is the 950-850 mb thickness.

3.2.2.3 Souza2 Model

The nomograms for the Souza1 model use the 1000-900mb thickness (T1090) and the 850-700mb (T8570) thickness for the forecasting of precipitation type. While T8570 does not appear in the equation for freezing precipitation it is the next most significant variable in the model. The temperature at 950mb showed relatively no skill in forecasting frozen precipitation, so it was not included in the nomograms. The 1000-900mb thickness is a measure of the low level under the influence of cold air damming while the the 850-700mb thickness measures warm air overrunning the cold air.. Figure 3.20 is the schematic of precipitation type. Figure 3.21 is the overall precipitation type nomogram and figure 3.22 is the precipitation subtype nomogram.

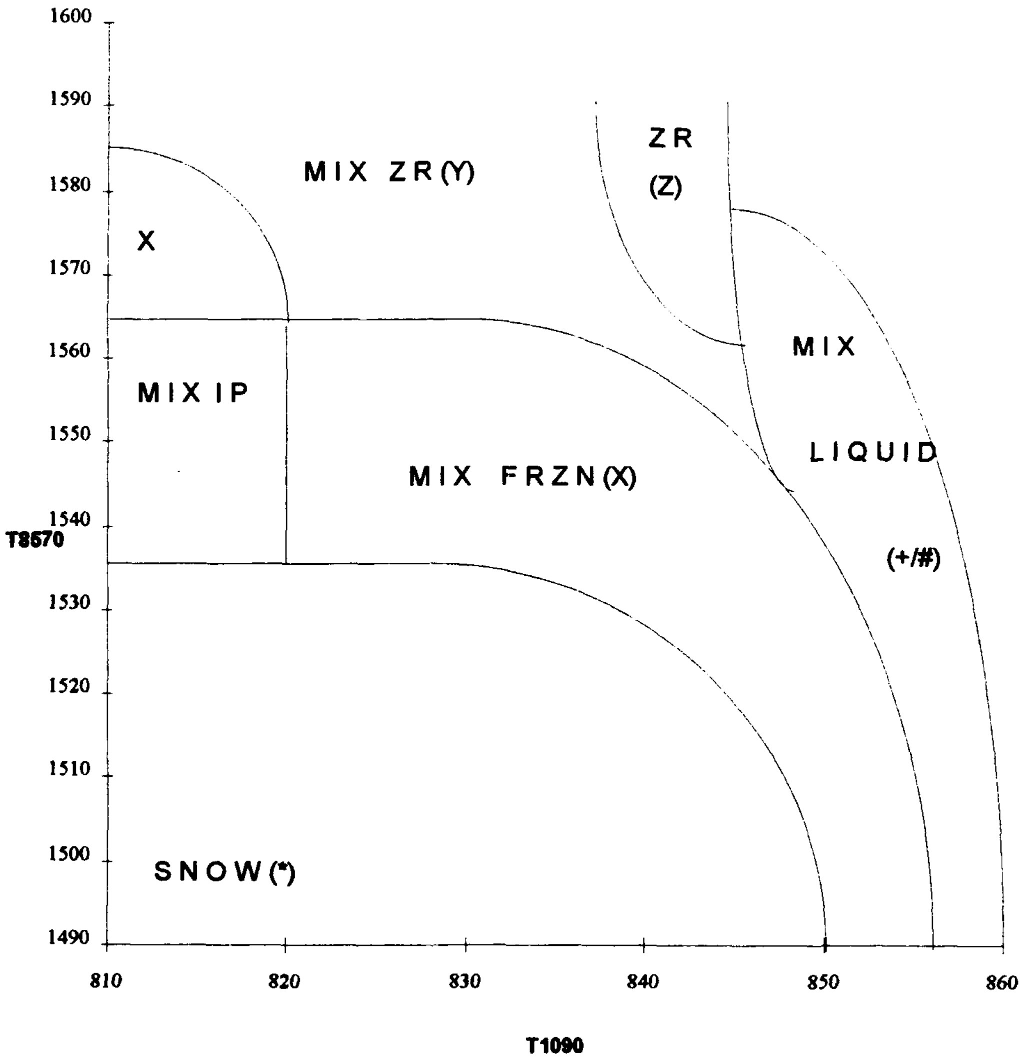

Figure 3.20. Same as figure 3.13 except for the Souza2 Model. T1090 is the 1000-900mb thickness. T8570 is the 850-700 mb thickness.

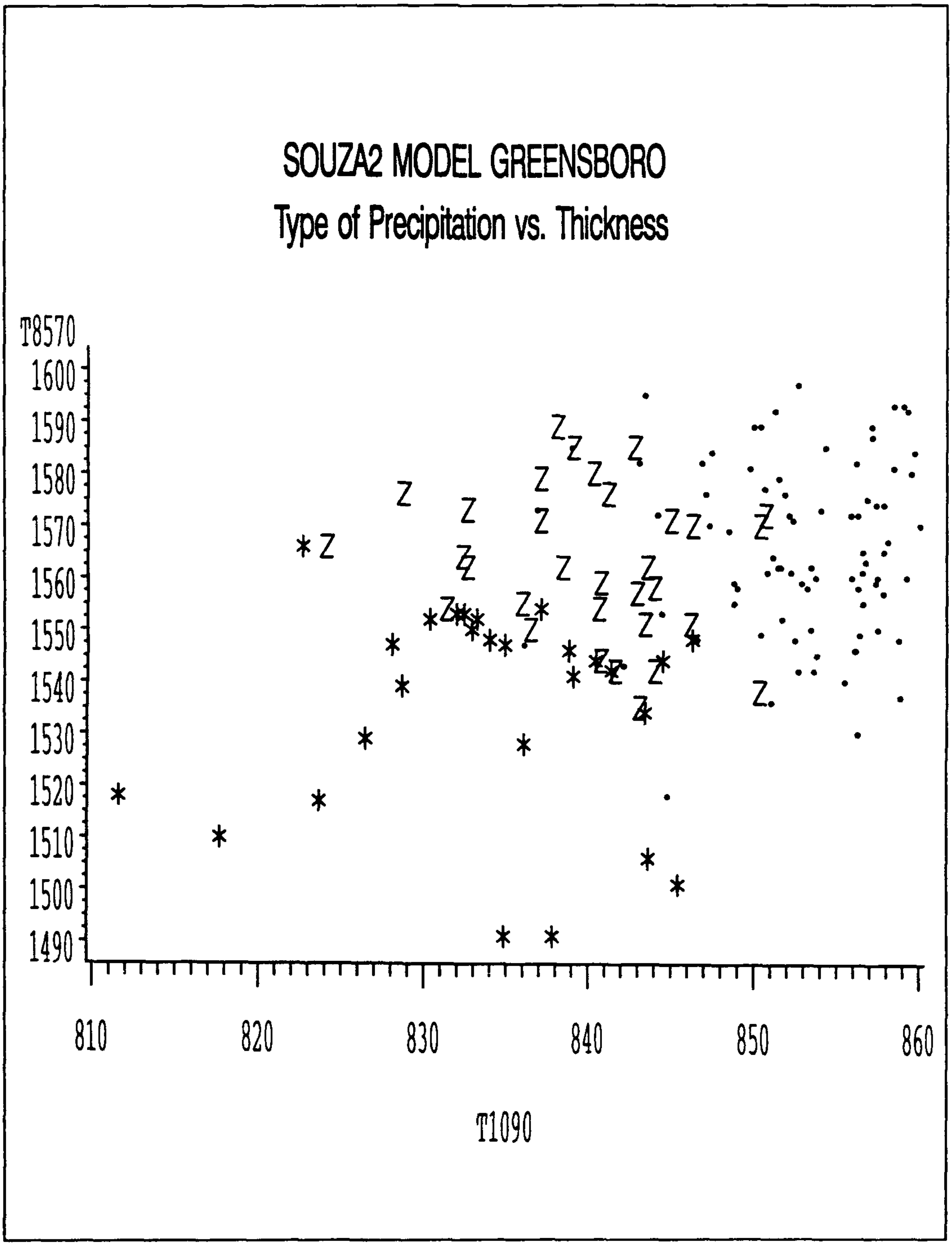

Figure 3.21. Same as figure 3.18 except for Souza2 Model. T1090 is the 1000-900mb thickness. T8570 is the 850-700 mb thickness.

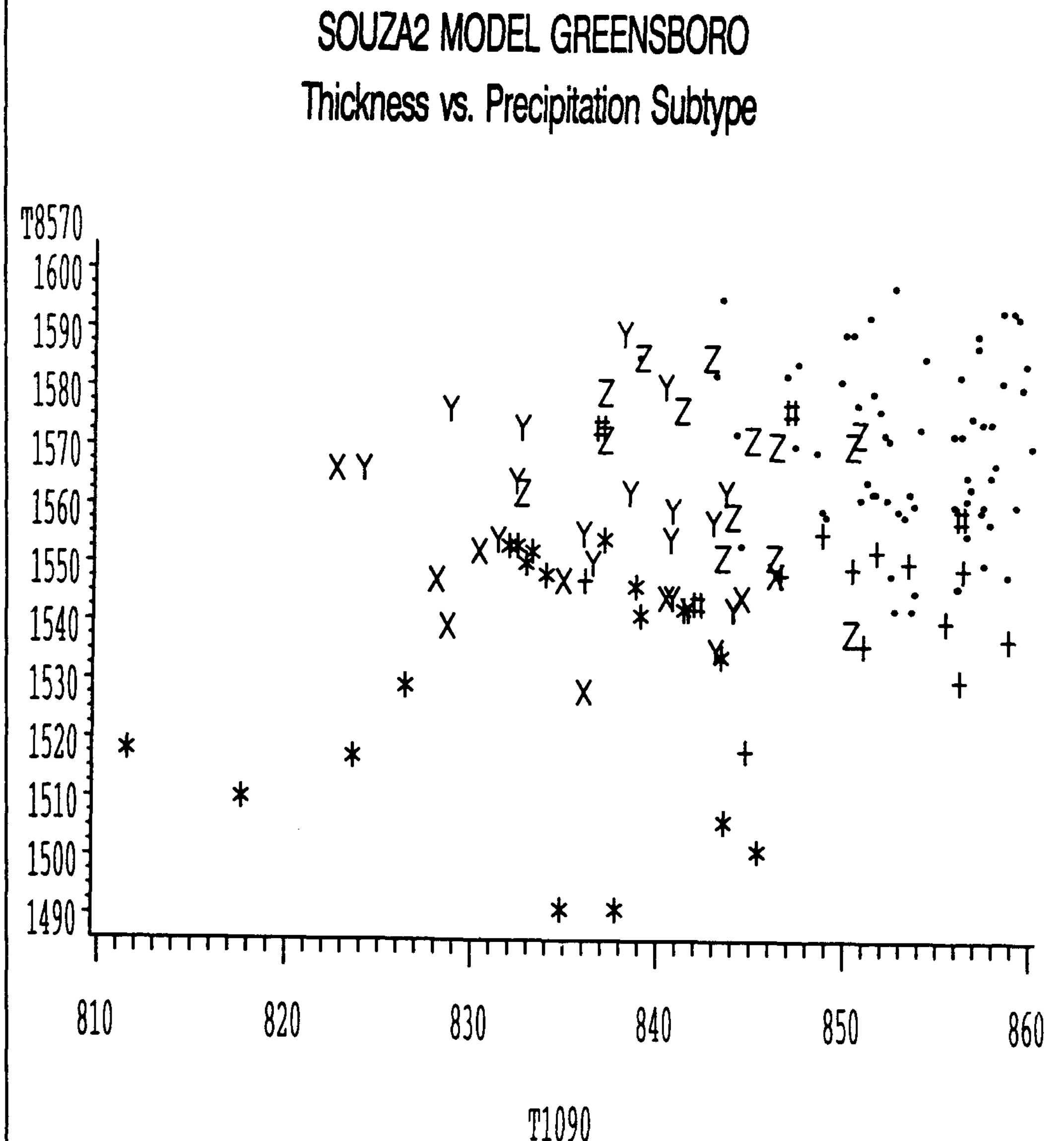

Figure 3.22. Same as figure 3.19 except for Souza2 Model. T1090 is the 1000-900mb thickness. T8570 is the 850-700 mb thickness.

3.2.3 Critical Values

The critical thickness values/ranges are derived visually from the TOP DOG nomograms and included the range of thickness values where a specific precipitation type occurred during the study period. They are consistent with those found in previous research as summarized in Chapter 1.4. The slight differences in thickness are due primarily to the shorter forecast period (6-hour versus 12-hour) and the larger data set of TOP DOG. Table 3.1 summarizes TOP DOG's critical thickness values.

TOP DOG's critical thickness for frozen precipitation compare favorably with Keeter and Cline (1991). They found a critical 1000-700mb thickness for frozen of <=2825m while TOP DOG's critical thickness is 2830m. TOP DOG's mixed precipitation critical 1000-700mb thickness of 2830-2850m compares favorably with their mixed precipitation window of 2825-2860m. Their critical 850-700mb thickness range of 1540-1560m for mixed precipitation is significantly narrower when compared with TOP DOG's critical thickness range of 1490-1590. A critical 1000-850mb thickness, as determined by Keeter and Cline, for mixed precipitation of 1280-1310m compares with TOP DOG's 1260-1310m. The latter differences can be accounted for by additional data (7 versus 20 years). Keeter and Cline's Freezing precipitation critical thicknesses of 1290-1310m (1000-850mb) and 1540-1560m (850-700mb) compare favorably with TOP DOG's 1260-1310m (1000-850mb) and 1555-1590m (850-700mb). TOP DOG's larger data set

provided an expanded Keeter and Cline's icy window (freezing and mixed precipitation).

TOP DOG compare favorably with Hanks, et al (1967) and their critical 1000-700mb thickness of 2840m for snow. Koolwine's critical 1000-850mb thickness for snow of 1314m is comparable to TOP DOG's 1310m. Differences between TOP DOG and Heppner (1992) critical thicknesses for frozen (snow) precipitation are also insignificant. Heppner's critical thicknesses of 1285-1300m (1000-850mb), 1529-1540m (850-700mb), and 2810-2830m (1000-700mb) are comparable to TOP DOG's respective critical thicknesses <=1310m, <=1555, <=2830m. Differences in the low-mid level partial thickness is due primarily to a difference between a period and snapshot forecast. Additionally, a larger data set leads to a broader critical threshold region.

TYPE OF PRECIP THICKNESS (M)	FROZEN	MIXED	FREEZING
700-500mb	<=2670	2550-2630	2595-2650
1000-700mb	<=2830	2830-2850	2850-2885
850-700mb	<=1555	1490-1590	1555-1590
1000-850mb	<=1310	1260-1310	1260-1310
950-850mb	<=895	870-910	890-910
1000-950mb	<=420	395-420	395-415
1000-900mb	<=845	820-845	830-845

Table 3.1. TOP DOG Critical Thicknesses (to nearest 5m) for GSO. Frozen indicates range of thicknesses for frozen (accumulating) precipitation. Freezing is same except for freezing precipitation. Mixed is the range of thicknesses where precipitation was primarily mixed. Overlaps with frozen or freezing indicate where emphasis should be placed.

3.3 The Southeastern United States' Piedmont Region

3.3.1 Summary of Regression Equations

The Keeter model is the best model for the regional prediction of frozen precipitation based on sensitivity. The Souza1 (with/without 500mb temperature) model is the best model for the regional prediction of frozen precipitation based on the value of the Schwartz Criterion. Figure 3.23 summarizes the sensitivities of each model. Figure 3.24 summarizes the value of Schwartz Criterion for the frozen precipitation regression equations in the SEUS PEIDMONT.

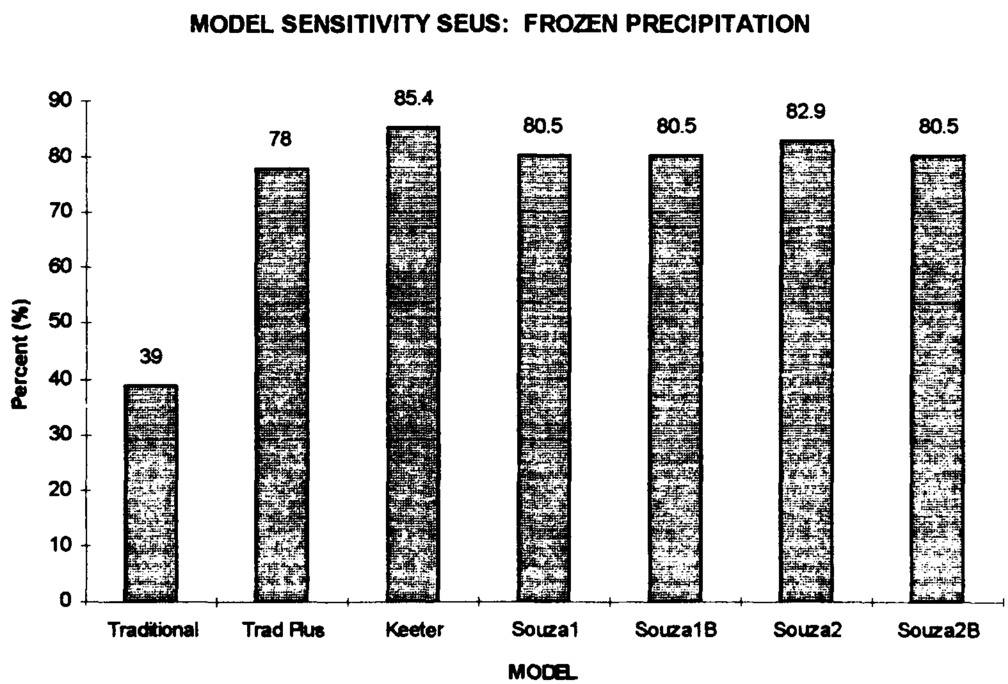

Figure 3.23 Model Sensitivity (Probability of Detection) for Frozen Precipitation in the SEUS. Sensitivity in percent (%). The Letter B in the Souza models indicates the model run without temperature (500mb frozen or 950mb freezing).

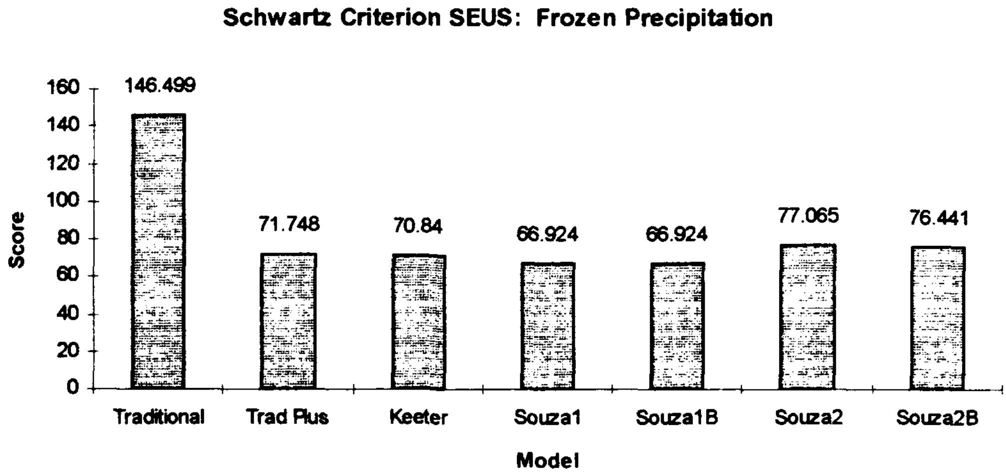

Figure 3.24. Schwartz Criterion for the Derived Regression Models for Differentiation of Frozen Precipitation from Liquid Precipitation. The letter B after a model indicates that the temperature variable was not included in the model. Lower values of the Schwartz Criterion indicate a better fitting model.

The Souza1 model with the temperature at 950mb included is the best model based on sensitivity for the forecasting of freezing precipitation in the PIEDMONT SEUS (See Figure 3.25). The same model is also the best (freezing precipitation) in terms of the Schwartz Criterion for assessing model fit (See Figure 3.26).

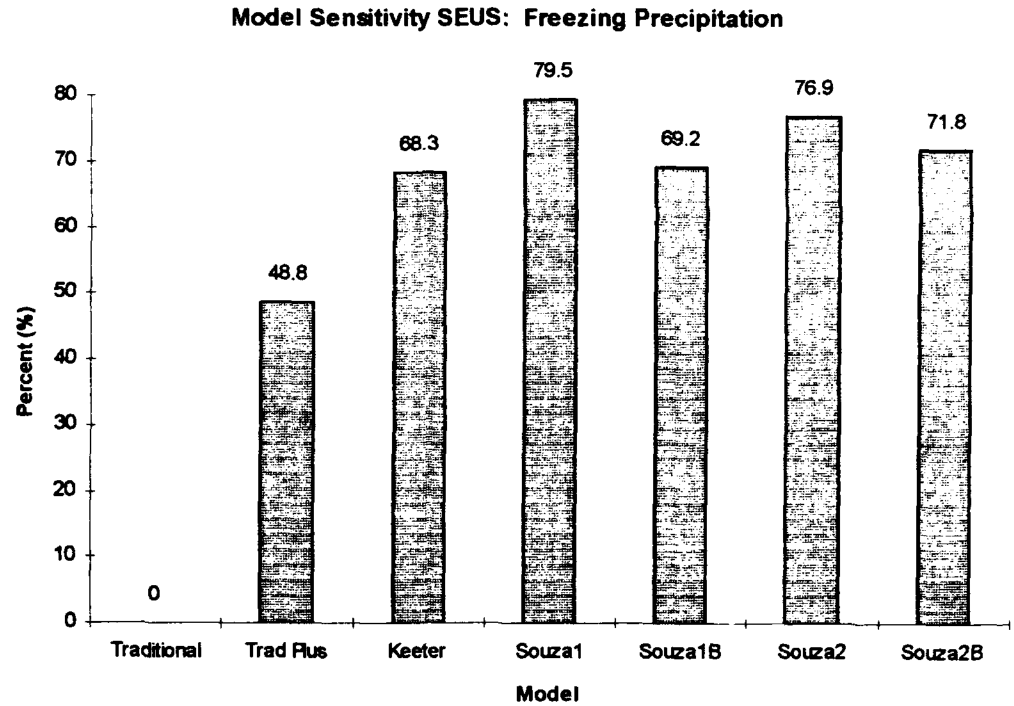

Figure 3.25. Same as Figure 3.23 except for Freezing Precipitation.

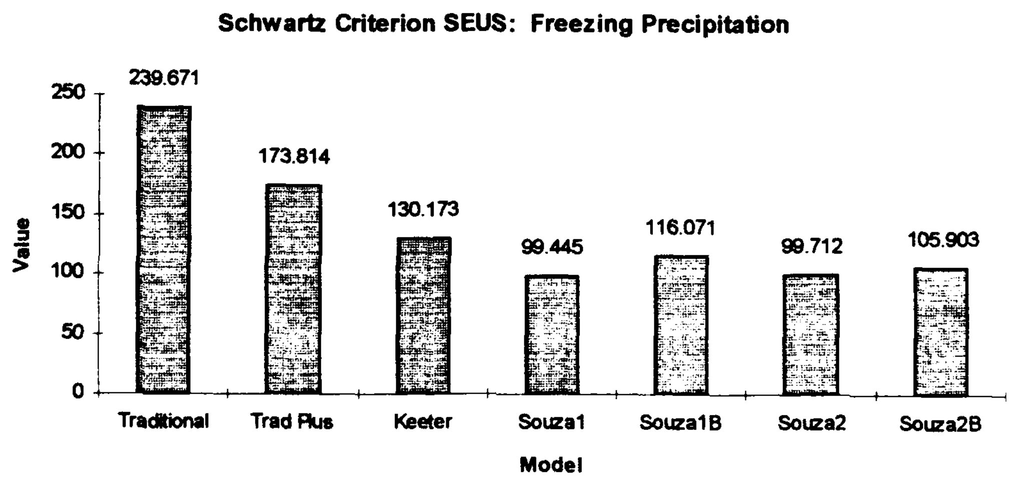

Figure 3.26. Same as 3.24 except for Freezing Precipitation.

The top model for forecasting frozen precipitation for the Southeastern United States' Piedmont is the Souza1 model (Eq. 3.14). The best freezing precipitation regression model is the Souza1 model (temperature at 950mb included: Eq. 3.15). These regression equations provide the conditional probability (p) of freezing or frozen precipitation forecasts. The precipitation type regression equations are:

FROZEN: Logit(p) = 306.4 + (-0.3458)T9585 **(3.14)**

FREEZING: Logit(p) = 75.7165 + (-0.0873)T9585 + (-1.1006)temp950 **(3.15)**

where T is the thickness between two levels in the atmosphere. The thickness of the 950-850mb layer (T9585) is a measure of the mixing or transition layer between the cold air dammed below 950mb and the warmer air overrunning the cold air through about the 850mb level. Temp950 is the temperature at 950mb and provides an indicator of the relative strength of the cold air dammed against the Appalachian mountains.

3.3.2 Summary Nomogram

The Souza1 model is the best model for predicting precipitation type for the southeastern United States' PIEDMONT Region. The nomogram is based on the 1000-950mb and 950-850 thicknesses. Figure 3.27 is the overall precipitation type nomogram. Figure 3.28 is the precipitation subtype nomogram. The nomograms for the Southeastern United States' PIEDMONT region, as expected, are comparable to those for Greensboro. Figures 3.27 and 3.28 could be used

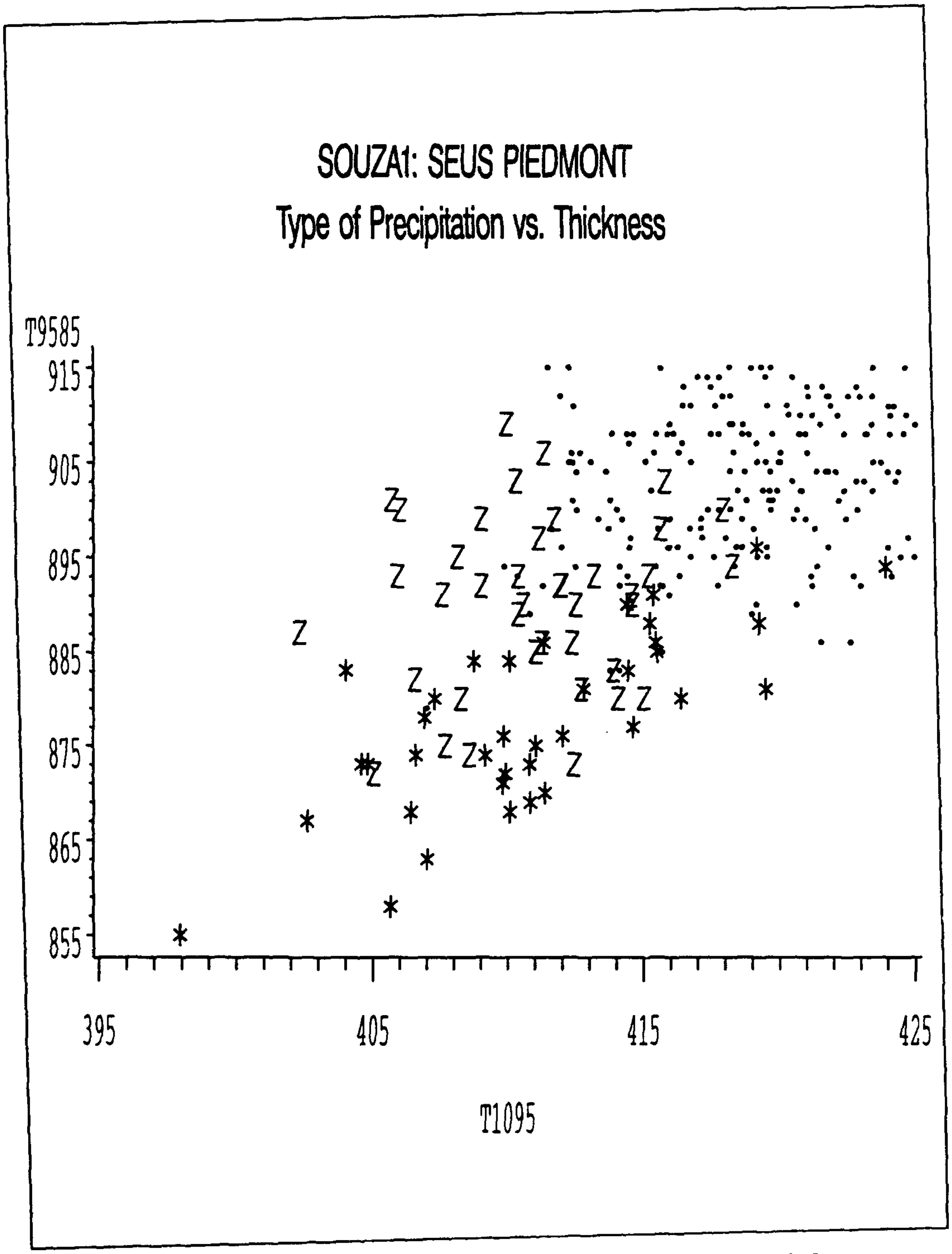

Figure 3.27. Same as Figure 3.20 except for the Souza1 model and the Southeastern United States' Piedmont.

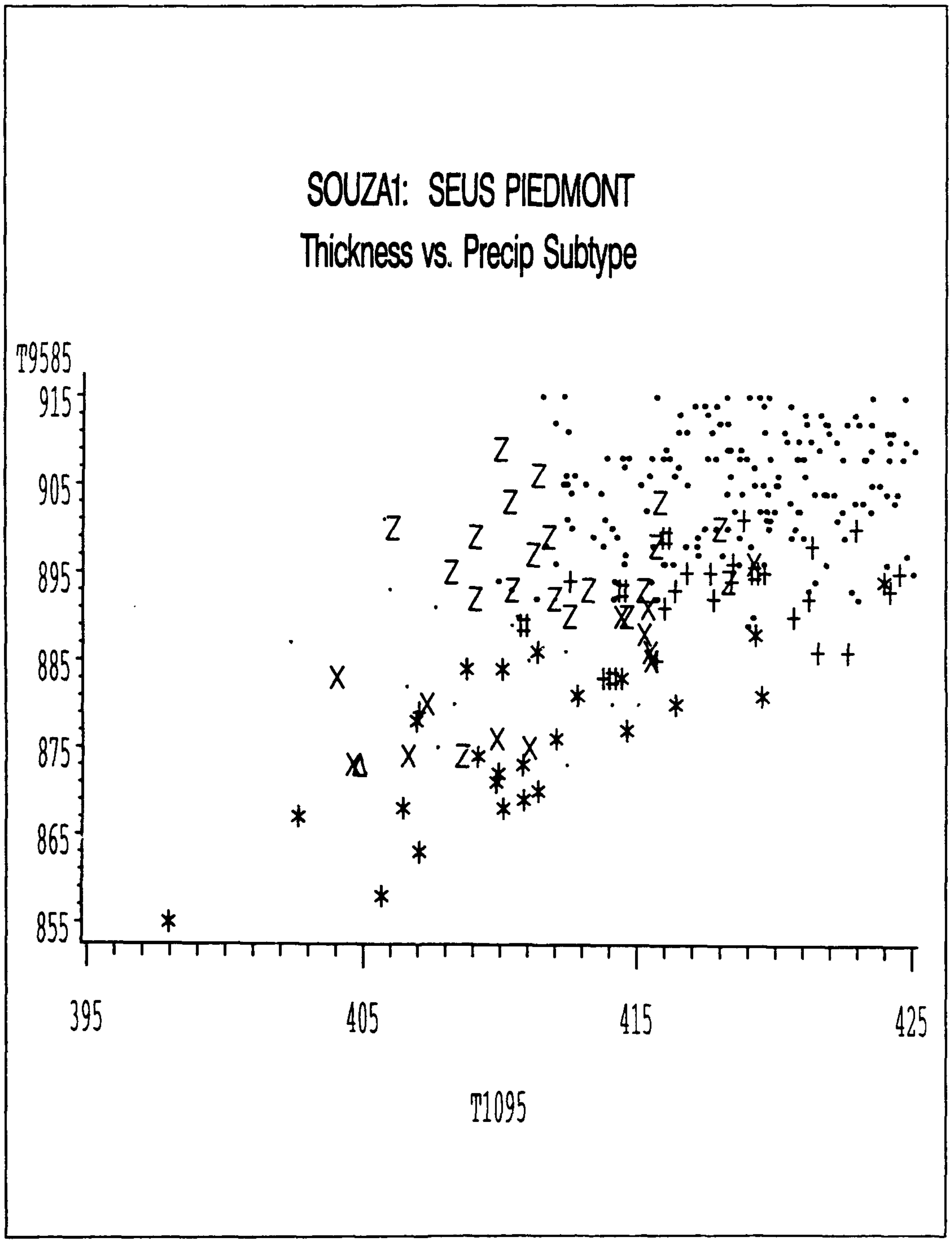

Figure 3.28. Same as Figure 3.21 except for the Souza1 model and the Southeastern United States' Piedmont.

operationally to forecast precipitation type at any Piedmont location under the effect of the cold air damming.

4 Case Study Greensboro, North Carolina: February 10/1200Z to 12/0000Z 1994

4.1 Overview

A classic cold air damming situation during the period 10 February 1200Z to 12 February 0000Z 1994 produced wide spread wintry precipitation throughout the southeastern United States. Greensboro, North Carolina (GSO) located in the Triad region of North Carolina was selected to illustrate the use of TOP DOG in the forecasting of precipitation type. Six forecast periods (6-hours each) were categorized according to precipitation subtype as defined in Chapter 2. Overall, 2 periods of accumulating frozen, 2 periods of freezing rain and 2 periods of liquid precipitation (as defined in Chapter 2) occurred during this case study and therefore provided an excellent test of TOP DOG's models.

A comparison of proposed forecast models shows that the Souza1 model outperformed all models for this case. Results of this case study confirm the selection of the Souza1 model for prediction of precipitation type based on the climatological study and development of TOP DOG's regression equations.

A classic cold air damming situation (as defined by Bell and Bosart, 1988) began to develop on the 10th of February 1994. Prior to the beginning of the case study's time period, a cold surface Arctic high pressure system was centered over Northern Michigan. Cold air at the surface began to slowly advect southward along the eastern slopes of the Appalachian mountains behind a cold front located over West Virginia that stretched eastward to the Atlantic coast. A quasi-stationary front

was located through northern Georgia northeastward through northern South Carolina.

Figure 4.1 shows the southeastern region's surface weather map on 10 February at 1200Z. At this point the temperatures in North Carolina were above freezing and all precipitation was in the form of rain. As a weak low pressure system moved eastward toward the South Carolina coast, cold air advection now enhanced by the surface low, brought a very cold and shallow arctic airmass into the North Carolina's Triad region where GSO is located. Cold air damming was well entrenched by 0000Z on the 11th (See Fig. 4.2) reaching a maximum depth at Greensboro of about 4500 feet by 0600Z. Simultaneously, a more defined low pressure center developed over the Gulf of Mexico and began to move northeastward over Louisiana. Strong moist southerly flow, associated with the newly developed surface low pressure system, first eroded the cold air west of the Appalachian mountains. East of the mountains the cold air remained firmly entrenched but by 1200Z on the 11th, the intensifying warm advection aloft gradually began to erode the low level cold air. This flow pattern is typical for the development of a broad transition zone (Keeter, et al. 1993) over the Triad region of North Carolina. At 1800Z on the 11th, the surface low pressure center was located over southwestern Georgia. Figure 4.3 shows that cold air damming in the Triad region of North Carolina had significantly weakened while the surface warm front has reached central South Carolina.

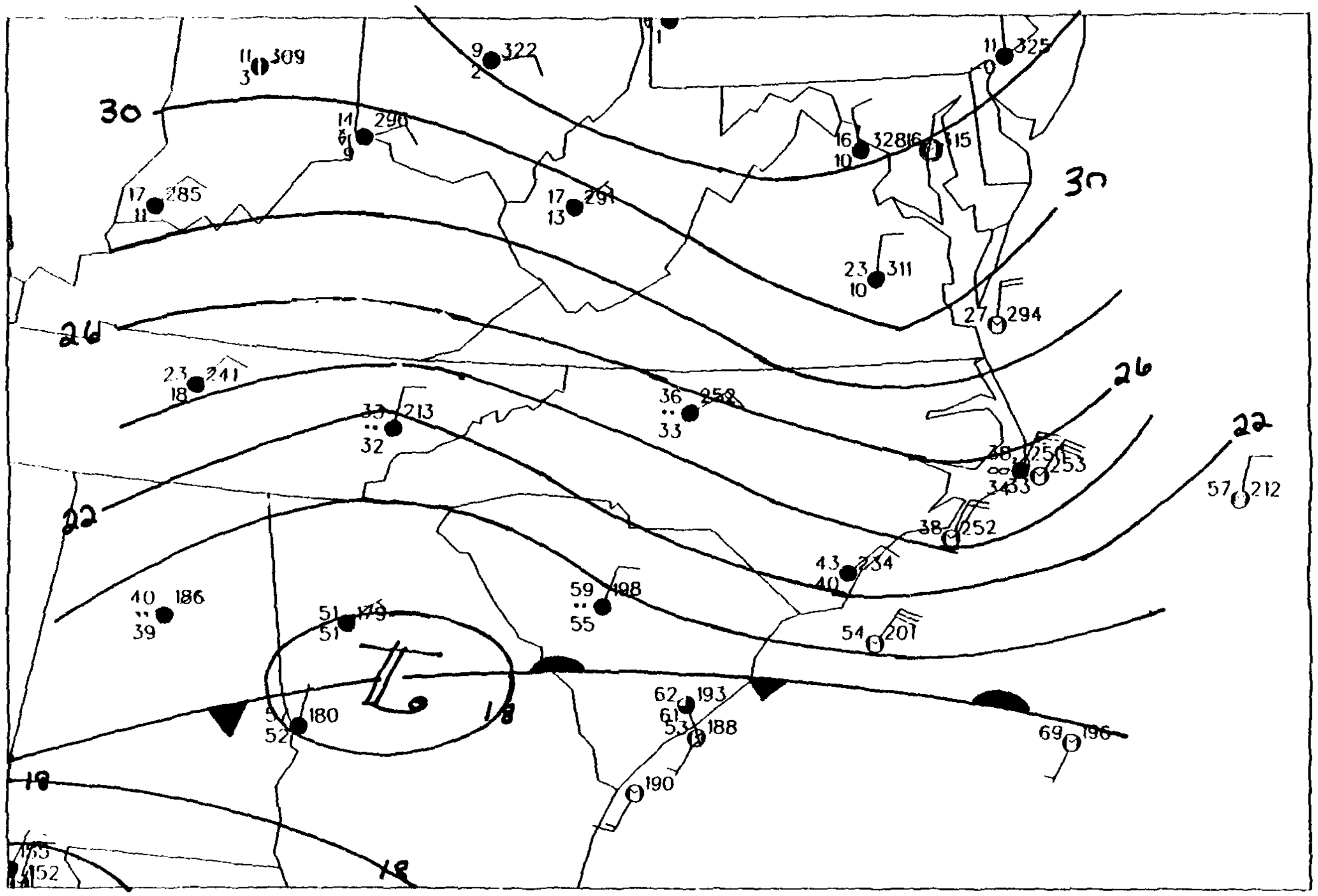

Figure 4.1. Regional Surface Analysis, 10 February 1200Z 1994. Pressure in millibars (mb). Surface Temperature and Dewpoints in degrees Fahrenheit. Wind in knots (Full barb is 10 knots).

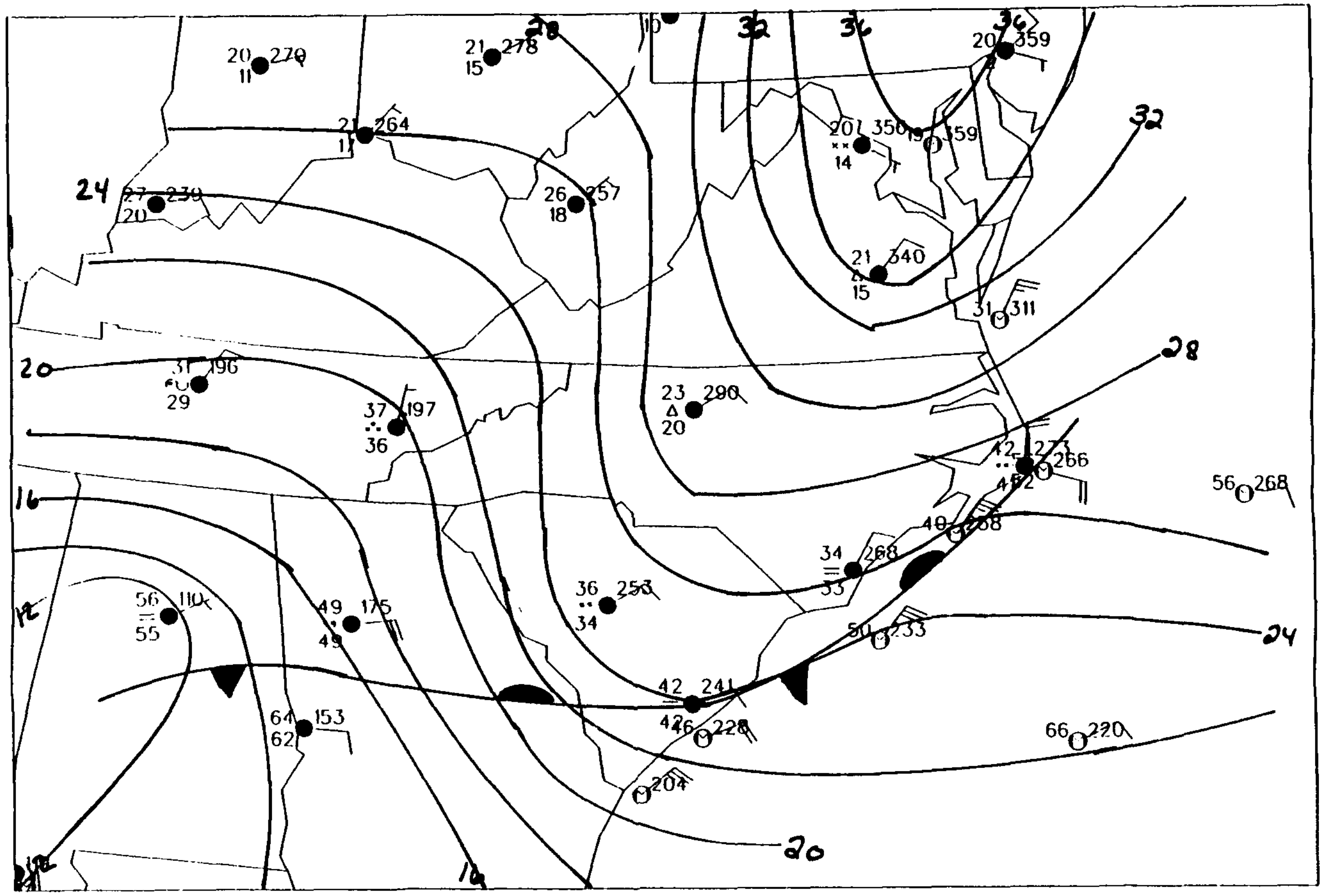

Figure 4.2. Same as Fig 4.1, except for 11 February 0000Z 1994

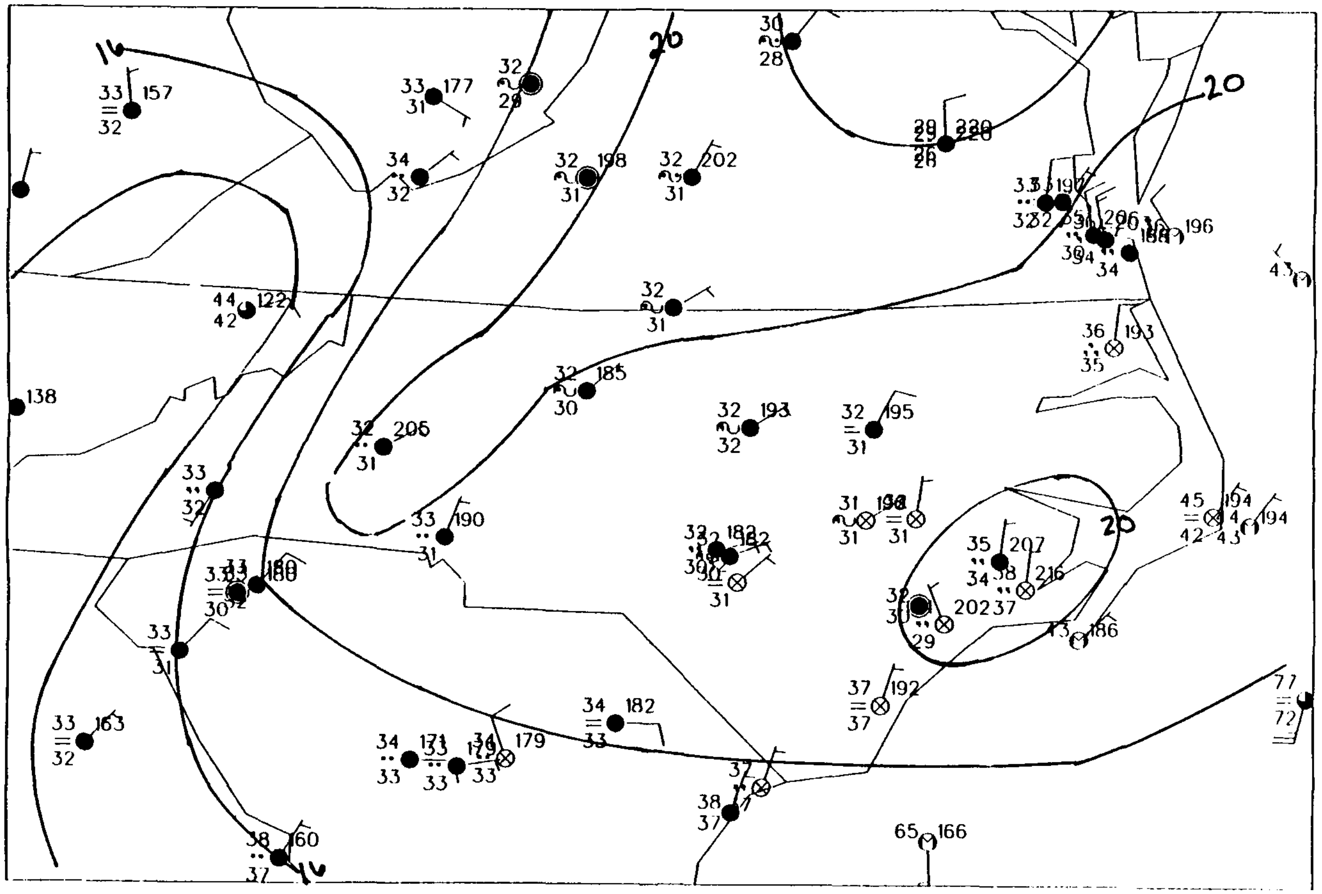

Figure 4.3. Sub-regional Surface Analysis, 11 February 1800Z. Pressure in millibars (mb). Surface Temperature and Dewpoints in degrees Fahrenheit. Wind in knots (Full barb is 10 knots).

4.2 Observed Conditions

4.2.1 Surface Conditions

Figure 4.4 is a surface meteogram for Greensboro, NC for the period 2000Z on the 10th until 2000Z on the 11th of February 1994. The meteogram shows the surface wind shift as the surface low lifts northeastward out of the Gulf and into Georgia. This wind shift to the east northeast (ENE) brought relatively warmer air from eastern North Carolina into the Triad Region. The surface temperature began to rise significantly concurrently with the wind shift. Snow amounts indicated on the meteogram are 12-hourly snow fall totals in inches. Three and 6-hourly precipitation totals are liquid equivalents.

Table 4.1 shows the precipitation subtype/type categories for this case study. All precipitation types that fell during the 6-hour period are also provided. Period 1 (10/1200-1800Z) was the transition into the cold air damming situation. Period 2 (10/1800-11/0000Z) is the period during which the surface temperatures cooled significantly as cold air advection streamed into GSO. Periods 3 (11/0000-0600Z) and 4 (11/0600-1200Z) are the during maximum cold air damming. Periods 5 (11/1200-1800Z0 and 6 (11/1800-12/0000Z) occurred during warm air advection which began to erode the cold air damming region as far west as the Triad.

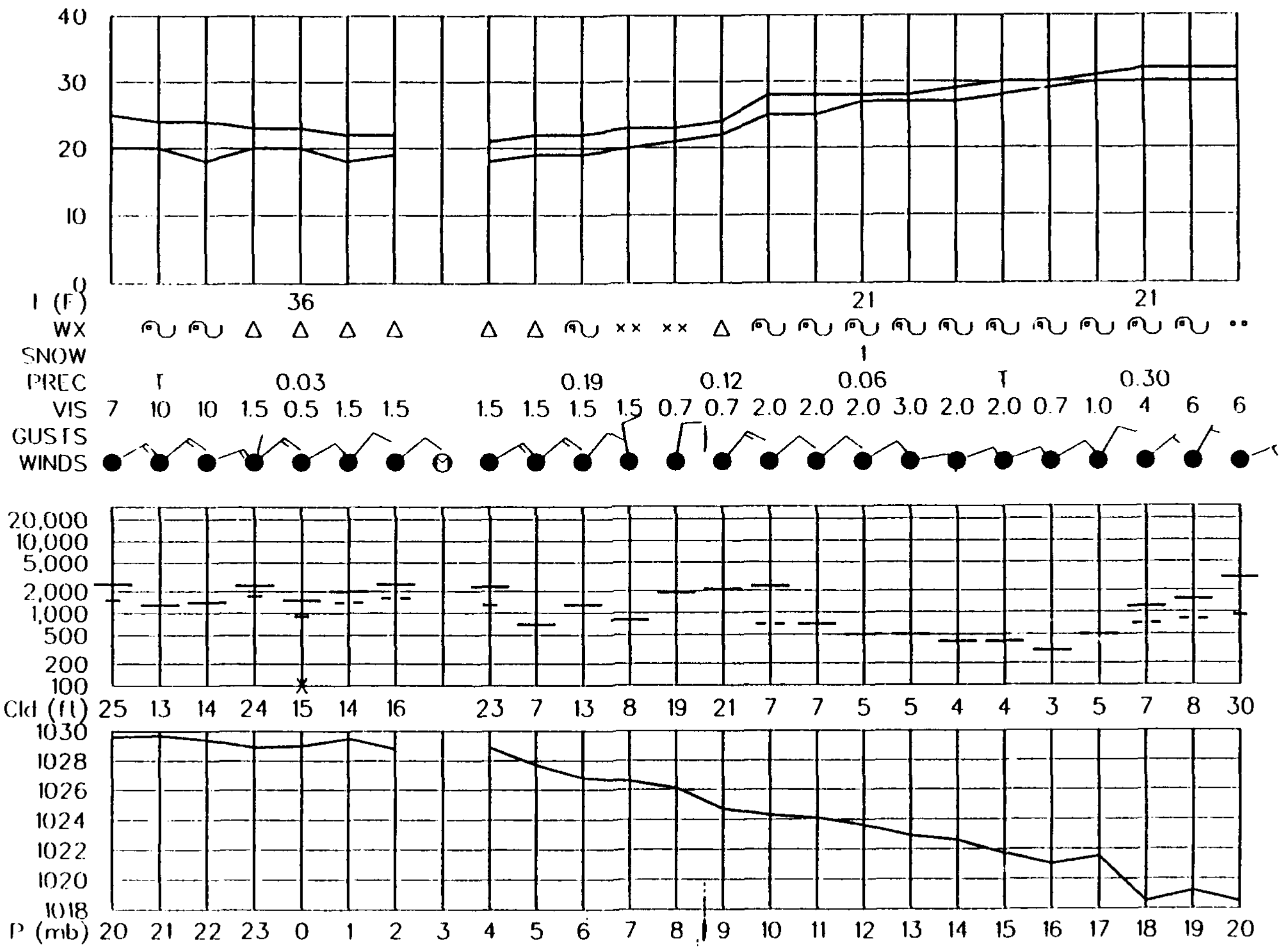

Figure 4.4. **Surface Meteogram for Greensboro, North Carolina valid from 2000Z on 10 February 1994 to 2000Z on 11 February 1994. Temperatures are in degrees F. Precipitation totals are in inches. Ceilings are in feet AGL. Pressure is in millibars.**

Period	*Date/Time Group (Z)*	*Precipitation Types During the Period*	*TOP DOG Precipitation Subtype (Nomograms)*	*TOP DOG Precipitation Type (Regression)*
1	10/1200-1800	RA, ZR, IP	Mixed Liquid with Freezing Rain	Liquid
2	10/1800-11/0000	ZR, IP	Freezing Rain with frozen	Freezing Rain
3	11/0000-0600	IP, ZR	Mixed Frozen	Frozen
4	11/0600-1200	S, IP, ZR	Mixed Frozen	Frozen
5	11/1200-1800	ZR, ZL	Freezing Rain	Freezing Rain
6	11/1800-12/0000	ZR, ZL, RA	Mixed Liquid with Freezing Rain	Liquid

Table 4.1. TOP DOG Precipitation Type Classifications. Types are defined as follows: ZR: Freezing Rain; S: Snow; ZL: Freezing Drizzle, IP: Ice Pellets; RA: Rain. TOP DOG types/subtypes as defined in tables 2.3 and 2.4.

4.2.2 Upper Air Conditions

Tables 4.2 and 4.3 summarize the upper air conditions as measured by thickness values for the time periods during this case. During the entire period of this case the temperature at 950mb, the hypothetical top of cold air damming as defined by Bosart and Bell (1988), remained below freezing. Figure 4.5 illustrates a typical cold air damming situation sounding for the Triad region of North Carolina.

DT SOUNDING	T1050	T1085	T8570	T7050	T1070
10FEB94:12:00	5502	1309	1565	2628	2874
10FEB94:18:00	5489	1285	1574	2630	2859
11FEB94:00:00	5508	1288	1585	2635	2873
11FEB94:06:00	5521	1289	1597	2635	2886
11FEB94:12:00	5546	1303	1597	2646	2900
11FEB94:18:00	.	1317	1590	.	2907

Table 4.2. Thickness Values (m) valid at sounding times (Z) indicated. T1050 is the 1000-500mb thickness. T1085 is the 1000-850mb thickness. T8570 is the 850-700mb thickness. T7050 is the 700-500mb thickness and T1070 is the 1000-700mb thickness.

DT SOUNDING	T1095	T9585	Temp 950	T9085	T1090
10FEB94:12:00	413	896	-1	464	845
10FEB94:18:00	403	882	-7.5	462	823
11FEB94:00:00	401	887	-8.5	466	822
11FEB94:06:00	400	889	-7.5	466	823
11FEB94:12:00	406	897	-6.5	471	832
11FEB94:18:00	407	910	-3	472	845

Table 4.3. Thickness Values (m) and Temperatures (C) used in TOP DOG's Souza models. T1095: 1000-950mb thickness. T9585: 950-850mb thickness. Temp 950: Temperature at 950mb. T9085: 900-850mb thickness. T1090: 1000-900mb thickness.

4.3 Traditional and Current Forecast Techniques

The traditional forecasting method to differentiate snow (frozen precipitation) failed in this case. Table 4.2 clearly shows that the traditional 1000-500mb threshold (5400m as defined by Penn, 1957 and Lamb, 1955; 5340m along the east coast as defined by Bluestein (1993) and Heppner (1992)) for frozen precipitation is never reached during the time period of this case. Trexler, et al (1994) notes that during the periods of freezing and frozen precipitation at GSO, the

1000-500mb 5400m thickness line was located over West Virginia eastward to the Atlantic coast. The '540' line was located well to the north of the Triad during the entire case study period. These results confirm that the 1000-500mb thickness is too crude an indicator for the forecasting of frozen precipitation in the southeast.

Keeter and Cline (1991) hypothesized that only liquid precipitation is expected when the 1000-700 mb thickness exceeds 2860m. Hanks, et al (1967) proposed a critical thickness of 2840 for the same layer. In this case, the 1000-700mb thickness exceeded Keeter and Cline's critical value for five of six possible time periods, including both cases of frozen precipitation, and also that of Hanks, et al's during all periods. Use of the 1000-700mb thickness did not do significantly better than the traditional approach in this case.

Keeter and Cline (1991) also noted that the 1000-850mb thickness in conjunction with the 850-700mb thickness offers a better picture for the forecasting of frozen and freezing precipitation. A critical 1000-850mb thickness of between 1280 and 1290 m was proposed by the authors for a forecast of measurable frozen precipitation along with a corresponding 850-700mb critical thickness of between 1540 and 1560m. In this case the 850-700mb thickness always exceeded 1574m (see Table 4.3) during the periods of freezing rain and frozen precipitation. However, the 1000-850mb thickness did fall in their proposed measurable frozen precipitation range for three periods (2-4), two of which experienced measurable frozen precipitation (3 and 4).

Similar results were found for freezing precipitation. Trexler, et al (1994) found that the frozen-freezing-rain boundary corresponded to the 1310m 1000-850mb thickness line for the entire southeastern United States. West of the Appalachian mountains the zone of transition was found by Trexler, et al to correspond with the 1550m 850-700mb thickness line. Keeter and Cline (1991) proposed that this zone would be associated with a thickness for this level of 1540-1560m. East of the Appalachian mountains, in the region of cold air damming this relationship did not hold true in this case.

The Skew-T Log P diagram for GSO at 0600Z (Fig 4.5) on the 11th shows that the top of the cold layer is at about 950-925mb. Recall that this time period is also the time period that the cold air damming reaches its maximum. The cold layer is defined by decreasing temperature or isothermal with height and a northeasterly wind direction. The warm layer can be identified by a wind from the southwest. The Skew-T Log P shows the top of the cold layer at approximately 930mb. Thus in this case, the 1000-850mb layer includes both the cold layer and the warm layer driving precipitation type formation. The thickness for the 100-850mb layer therefore, averages the cold and warm layers and clearly is too crude a tool for the forecasting of precipitation type in this case. Better measures of the strength of the cold air and of the warm air overrunning the dammed cold air are crucial to forecasting precipitation type in this region.

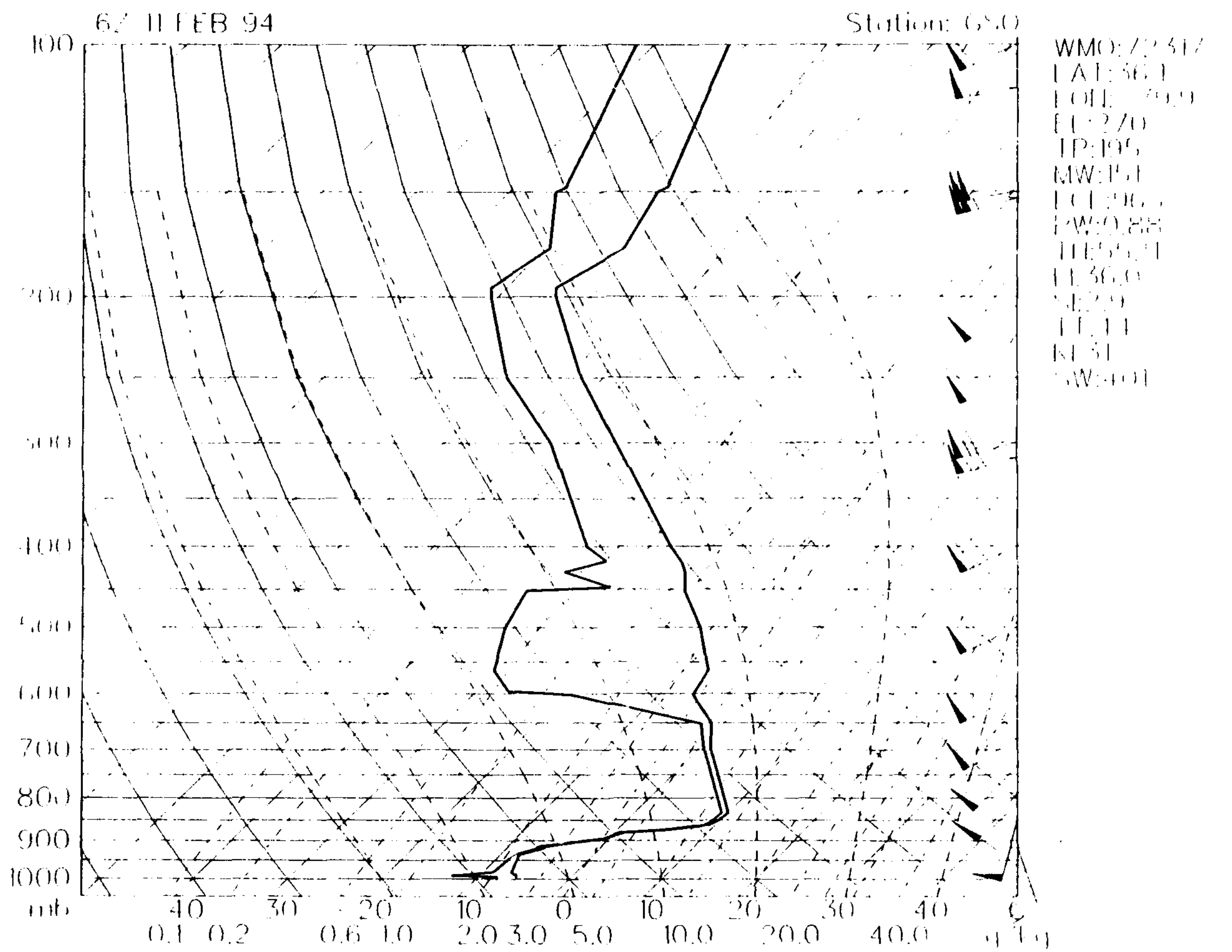

Figure 4.5. Skew-T Log P diagram for Greensboro, NC at 0600Z on the 11th of February 1994.

4.4 TOP DOG Applied

4.4.1 Comparison of Model Predictions: Regression

The top prediction model (regression) for frozen precipitation at Greensboro, NC as shown in Chapter 3 is the Souza1 model. This model was designed to take into account cold air damming by the use of low level thicknesses such as the 1000-950mb (cold layer) and 950-850mb (warm or transition layer) thicknesses. The Souza1 regression model forecasted frozen precipitation (see Figures 4.6 and 4.7) in only time period 2 (10/1800-11/0000Z). The Souza1 model did not reach the forecast threshold (50% conditional probability) for time periods 3 and 4 (11/0000-11/0600-11/1200Z) during which measurable frozen precipitation fell. Conditional probabilities exceeded 30% in period 3 and approached 20% in period 4. Overforecasting of frozen precipitation in time period 2 is primarily due to the fact that the surface was still relatively warm and frozen precipitation originally melted on contact with grassy surfaces while frozen and freezing precipitation accumulated on other exposed objects such as bridges, railings, etc. A problem in forecasting accumulating ice pellets during periods 3 and 4 is due a lack of ice pellets-sleet only occurrences in the development data set.

Figure 4.6 shows Keeter and Souza2 (with/without temperature at 500mb) models forecast accumulating frozen precipitation during the period 10/1800-11/1200Z. . The Souza2 model (with and without the 500mb temperature) forecasts frozen precipitation only during the period 10/1800-11/0000Z. The

conditional probabilities for the next time period were slightly below the prediction threshold of 50%. The Table 4.1 showed that measurable frozen precipitation occurred during the 11/0000-11/1200Z time period while freezing precipitation fell during the 10/1800-11/0000Z and 11/1200-1800Z time periods.

The Souza1 (with temperature at 950mb included) was the top prediction model for freezing precipitation (threshold conditional probability .40 or 40%). The model forecasts freezing precipitation for time periods 2-6 during which frozen or freezing precipitation occurred during all periods except in period 6 (freezing rain mixed with rain). The model also indicated a significant probability (>20%) of freezing precipitation during period 1 (rain changed to freezing rain during this period).

Figure 4.7 compares the TOP DOG models freezing precipitation forecasts. Again the Traditional and Traditional Plus models are not included in figure 4.7. The Keeter model shows its sensitivity to mid-level warm air advection well above the cold air dome by its dramatic drop off in probability of freezing precipitation from periods 4 to 6. All models except the Souza2 model and the Keeter model (time period 6) are similar in their predictions.

Precipitation type probability forecasts for GSO based on the Souza1 model are found in table 4.8. Based solely on regression equations, the model predicts freezing precipitation during periods 2-6. The predicted conditional probability of frozen precipitation meets the forecast threshold during period 2. In this case, the regression equations provided the forecaster with a fair forecast tool. The

occurrence of ice pellets appears likely during periods when freezing and frozen precipitation both exceed or are close to their prediction thresholds. TOP DOG's nomograms allow the forecaster to clarify and qualify conditional probability forecasts.

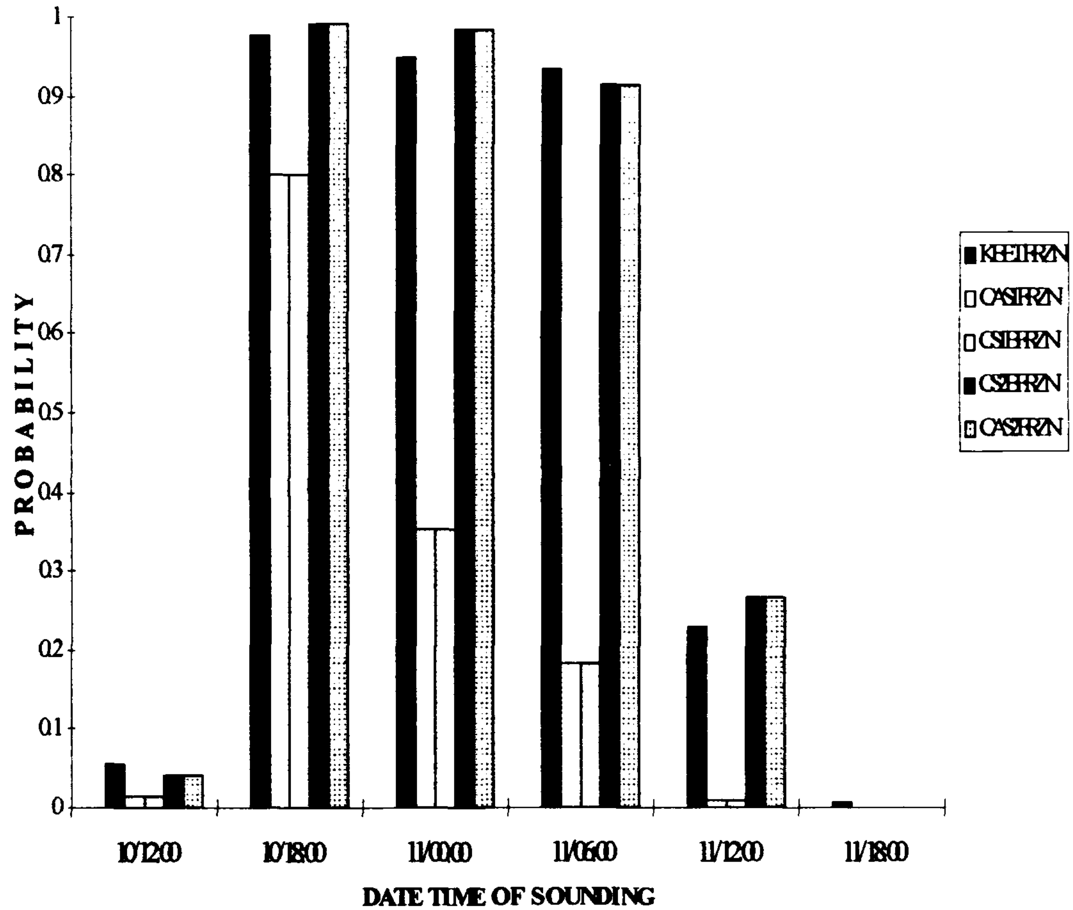

Figure 4.6. Conditional Probability of Frozen Precipitation Type for the TOP DOG Prediction Models (Regression equations: 3.2.1.3-3.2.1.5). KEET is the Keeter model. CAS1 is the Souza1 Model with 500mb temperature. CS1B is the Souza1 model without the 500mb temperature. CAS2/CS2B are the same as CAS1/CS1B but for the Souza2 Model.

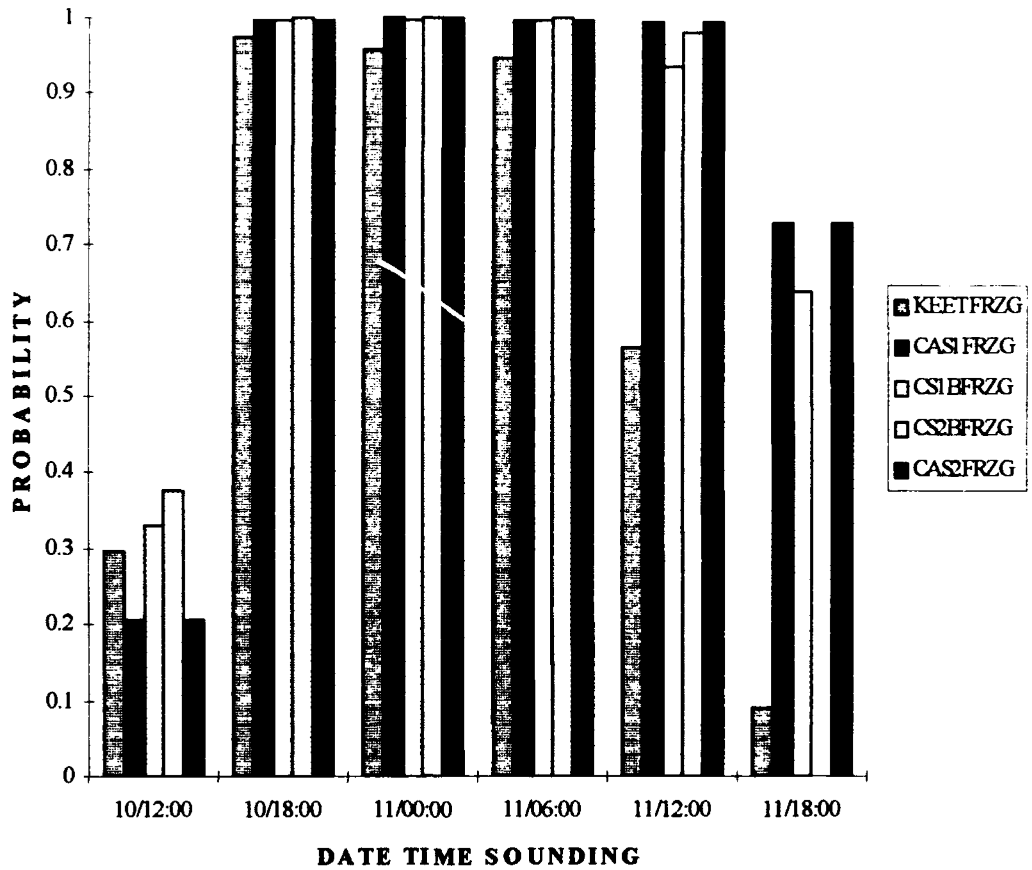

Figure 4.7. Conditional Probability of Freezing Precipitation Type for the TOP DOG Prediction Models (Regression equations: 3.2.1.3-3.2.1.5). KEET is the Keeter model. CAS1 is the Souza1 Model with 950mb temperature. CS1B is the Souza1 model without the 950mb temperature. CAS2/CS2B are the same as CAS1/CS1B but for the Souza2 Model.

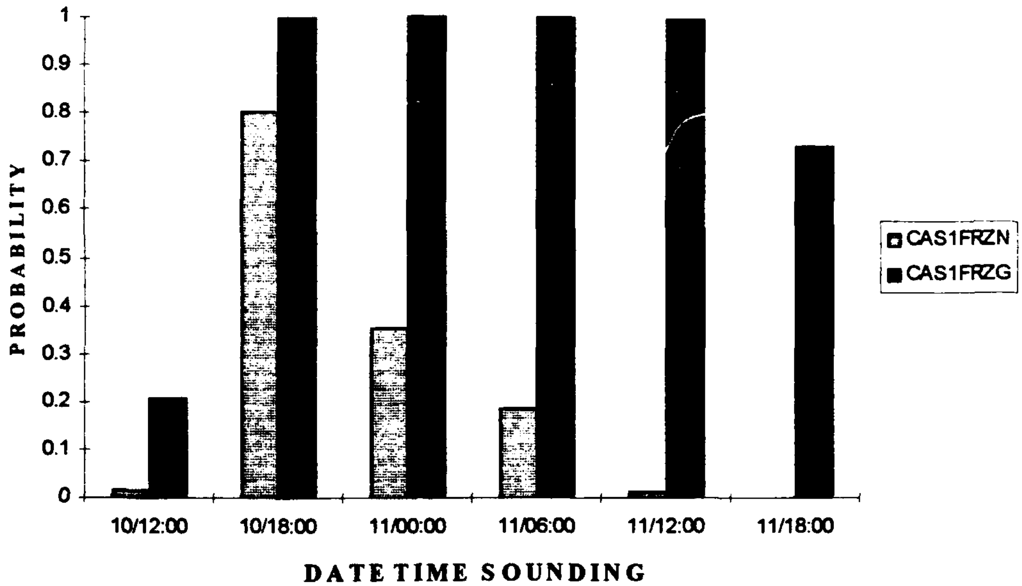

Figure 4.8. Conditional Probability of Freezing and Frozen Precipitation for the SOUZA1 (See 3.2.1 for equations)includes temperature at 950mb for freezing) model. CAS1FRZN: Probability of Frozen. CAS1FRZG: Probability of freezing.

4.4.2 Comparison of Keeter and Souza1 Nomograms

As shown by Keeter and Cline (1991), nomograms provide the forecaster with a graphical understanding and quantification of the physical processes occurring in the atmosphere. The Keeter model nomogram and Souza1 nomograms are compared to illustrate the importance of the lowest levels during this case. The Souza1 nomogram correctly forecasted the precipitation type in 5 of 6 time periods. The Keeter nomogram correctly forecasted only 2 (definite) up to possibly 3 of 6 time periods.

Figure 4.9 illustrates the predictions produced by the TOP DOG nomogram that expands on the nomogram proposed by Keeter and Cline. For the first period, the nomogram correctly indicated that mixed liquid precipitation should be expected. A relatively high 1000-850mb thickness and 850-700mb thickness illustrates the atmosphere prior to the onset of significant cold air damming. In the second period the nomogram correctly forecasts freezing rain with mixed frozen. By period 3 the nomogram based forecasts begin to deviate from the observed. While the nomogram indicates a continuation of freezing rain with mixed (non-accumulating) frozen, ice pellets accumulated during this and the next period. The period 4 nomogram forecast is more nebulous due to its extreme values based on the development data set; a forecast of freezing rain mixed with frozen or mixed liquid or liquid precipitation could be deduced by the forecaster. Again in period 5, an unclear forecast of either freezing rain or mixed liquid or liquid precipitation is

possible. Actually, freezing rain occurred during this period. The nomogram correctly forecasts liquid precipitation in period 6.

The nomogram based on the Souza1 model (Figure 4.10) significantly improved the precipitation type forecasts for this case. The only period during which the nomogram based forecast differs from the observed is during period 2. During this time period, cold air damming was developing and strong cold air advection was occurring in the region. Accumulations of frozen precipitation during this period were delayed due to a relatively warm ground. The nomogram clearly illustrates the relationship between the lowest layers (1000-950mb thickness) and the transition or warmer layer above the cold air. As the 1000-950mb thickness decreased concurrently with the 950-850mb thickness a forecast of frozen precipitation was prudent. As warm air overrunning intensified at the level immediately above the cold air dome, the precipitation fell through this region that provided a warm and deep melting layer sufficient to melt snow to liquid upon reentry into the cold air dome the droplets had insufficient time to refreeze before they reached the surface. This leads to a forecast of freezing precipitation. As the lower layers warmed, the freezing precipitation gradually mixed with and changed to rain. TOP DOG's Souza1 model nomogram provided an excellent forecast tool for this case. Additionally, it provided an understanding of the atmospheric processes occurring during each forecast period.

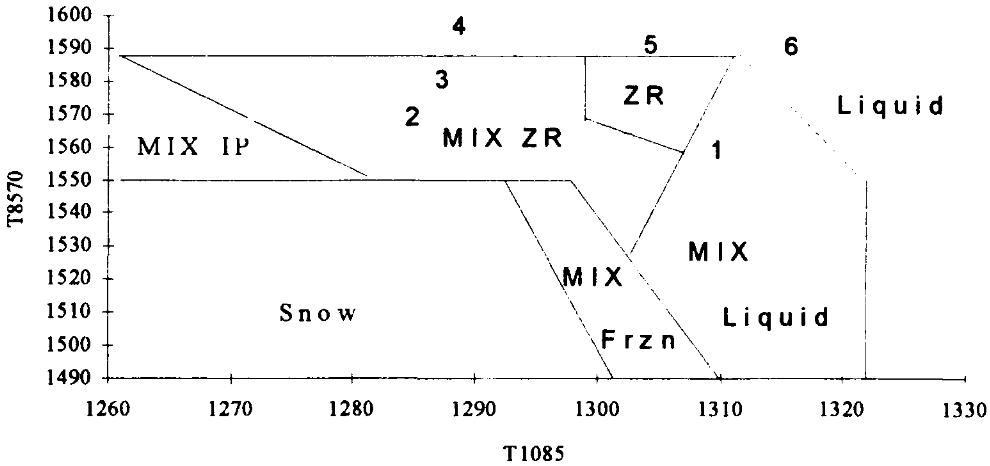

Figure 4.9. TOP DOG Nomogram for the Keeter Model. T1085 is the 1000-850mb thickness; T8570 is the 850-700mb thickness. Numbers 1-6 indicate period (as defined in Table 4.1) thickness values plotted for the case study time period.

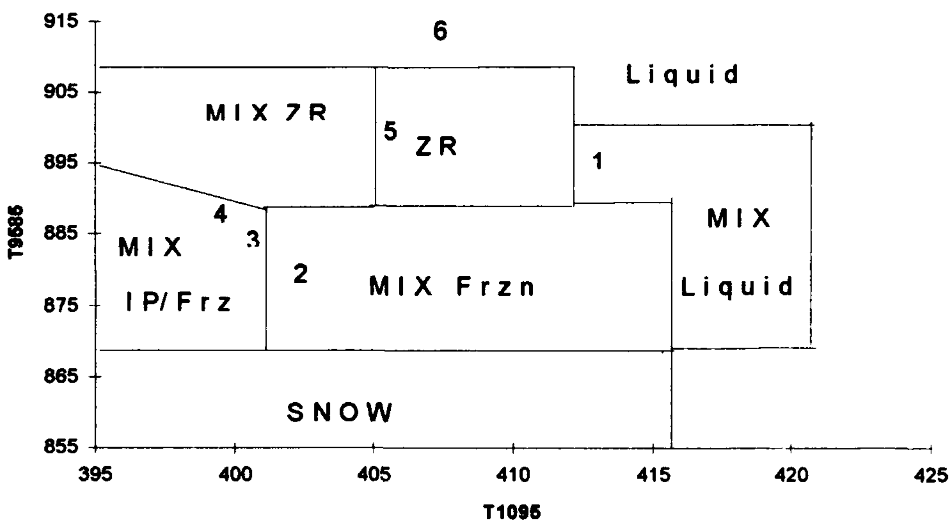

Figure 4.10. TOP DOG Nomogram for the Souzal Model. T1095 is the 1000-950mb thickness; T9585 is the 950-850mb thickness. Numbers 1-6 indicate period (as defined in Table 4.1) thickness values plotted for the case study time period.

4.5 Summary

The period of 10 February 1200Z to 12 February 0000Z provided excellent results and illustrate the potential ability of TOP DOG to forecast precipitation type, via the use of its regression equations and nomograms, during a classic cold air damming event affecting Greensboro, North Carolina. A comparison of forecast results showed that the Souza1 model was an excellent forecast model for predicting precipitation type during this period. One test case, however, provides only a limited evaluation of the TOP DOG models.

As was illustrated here, forecasters must rely on an integrated forecast approach and not rely on one forecast method too heavily. No one technique can replace a thorough understanding of the ongoing atmospheric processes. For example, this case study reinforced the importance of evaluating and separating the cold air damming layer and the warm overrunning layer to understand and correctly forecast precipitation type.

5 Summary, Conclusions, and Suggestions for Future Research

5.1 Summary

Precipitation type forecasting in the Southeastern United States, where wintry precipitation is relatively infrequent and typically occurs as a mix of wintry precipitation types, presents a significant challenge to the operational forecaster. Additionally, forecasters must increasingly provide more specificity amongst mixed precipitation types in today's forecasts. An overview of current and previous precipitation type forecasting techniques such as NGM MOS (Erickson 1994) and LOG/PT (Keeter and Cline 1991) is included.

Forecast techniques available to the operational forecaster should be sophisticated enough to account for a thorough understanding of forecasting precipitation type but simple enough to be used in a timely and consistent manner. A powerful but easy to use supplement, the Type of Precipitation: Descriptive and Objective Guidance (TOP DOG), to current precipitation type forecasting techniques such as the NGM MOS and local forecast procedures, was developed to help more completely specify mixed precipitation cases common to the Southeastern United States during cold air damming events.. TOP DOG consists of regression equations providing conditional probabilities of a precipitation type and nomograms for differentiation of precipitation subtypes based primarily on the use of partial thicknesses.

Tests of statistical significance, showing the importance of the lowest levels of the atmosphere and their associated thickness for the prediction of freezing

precipitation, are presented. Statistical (logistic regression) models are proposed and tested for their ability to predict frozen and freezing precipitation in the Southeastern United States. Results from regression equations for Greensboro, North Carolina are provided. Schematic nomograms were developed to simplify precipitation type forecasting. A simple case study was used to illustrate the use of TOP DOG during a prototypical cold air damming event.

5.2 Conclusions

Tests of significance (summarized in Table 2.6) for the prediction of frozen versus liquid precipitation at single stations in the Southeastern United States showed that further subdivision of thicknesses (e.g. 1000-700 mb) into partial thicknesses after subdivision of the 1000-500 mb thickness into the 1000-700 and 700-500 mb thicknesses did not improve the models forecasting capability. The lack of significance of further subdivision of thicknesses does not prove that the state of the atmosphere in the lowest part of the troposphere nearest the surface is not important. The 1000-700 mb (surface to about 10K feet) thickness appears to sufficiently take into account the section of the atmosphere where snow forms and falls. Inclusion of all potential predictors in the model adds additional complexity to the model that is not required to produce a quality forecast of frozen precipitation at these stations. The inclusion of the lower thicknesses (e.g. 1000-850.850-700 mb thicknesses) did not statistically improve the frozen precipitation forecast models for other stations.

Regionally, predicting frozen precipitation at inland southeastern United States stations (GSO/AHN), the addition of the 500 mb temperature was barely significant. While further subdivisions of thickness (after the 1000-700 and 700-500 mb partial thickness) was not significant for the SEUS, it was significant for the coastal stations (CHS/HAT) in the region. Subdivision of the 1000-700 mb thickness into the 1000-850 and 850-700 mb thickness was important for coastal regions. The 1000-850 mb thickness takes into account the strength of cold air in the lower levels while the 850-700 mb thickness explains the strength of warm air advection and whether the atmosphere is cold enough to maintain snow/frozen precipitation. The temperature at 500mb provides insight into the location of the upper level trough. If the temperature at 500mb is relatively high, the trough is typically to the west, If relatively low, the trough is roughly overhead.

For freezing precipitation, tests of significance showed that subdivision of the 1000-700mb thickness and the 1000-850 mb thickness were significant for the forecasting of freezing precipitation at stations in the southeastern United States. Bell and Bosart (1988) and Forbes et al (1987) noted that the cold air dammed along the eastern slopes of the Appalachian mountains extends upward to approximately 930 mb. Obviously, the 1000-950 mb thickness and the 1000-900 thickness represent the strength and depth of the cold air damming for inland stations in the region.

Regionally (See Table 2.9), the temperature at 950mb was significant. Again, the temperature at 950mb represents the strength and depth of the cold air dammed along the eastern slopes. No other potential predictors were significant.

Partial thicknesses (down to the level of cold air damming)when combined with only the temperature at 950mb provide a simple yet powerful model for the forecasting of precipitation type in the cold air damming regions of the Southeastern United States. The Souza1 model that includes the 1000-950mb thickness, 950-850mb thickness and 950mb temperature is the top model for the prediction of freezing and frozen precipitation at Greensboro, North Carolina deep in the climatological cold air damming region.

The period of 10-12 February 1994 was well handled by the Souza1 model. Models that did not include low level thickness did not perform well during this case of cold air damming.

5.3 Future Research

Additional detailed study of the cold air damming region during mixed precipitation events is needed to provide forecasters a better understanding of the physical processes. Scale analysis of the thermodynamic processes leading to local temperature change is needed to verify that advection dominates the change in local temperature during the precipitation event. Additional evaluation cases of TOP DOG's models are needed to verify it's usefulness. Further study of transition zones in the Southeastern United States is required.

The data set used in the development of TOP DOG should be expanded with data from future cases. Coastal station forecast models, due to the infrequency of frozen and freezing precipitation cases, could be improved significantly by expanding the time period of study. Inclusion of other partial thickness values (e.g. 1000-925mb) should be investigated as measures of cold air damming. Results from research into the modeling of cold air damming and precipitation physics in this region must be incorporated into the current and future numerical models as soon as results are verified.

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APPENDICES

7 APPENDICES

7.1 APPENDIX 1: Sample Forecast Wording for TOP DOG Precipitation Subtypes

SNOW (Subtype 1): Snow with accumulations of (fill in expected amount). Forecaster should include appropriate local warning/advisory information

MIXED FROZEN (Subtype 2): Snow with accumulations of (fill in expected amount) possibly mixed with ice pellets, freezing rain or rain at times(choose appropriate types based on nomogram) Forecaster should include appropriate local warning/advisory information

ICE PELLETS (Subtype 3) Ice Pellets (sleet) accumulating to (fill-in expected amount) (Forecaster should include appropriate local warning/advisory information)

FREEZING RAIN WITH MIXED FROZEN (Subtype 4): Freezing rain mixed at times with snow or ice pellets. Significant accumulations cf ice on exposed surfaces (roads, trees, etc.) but little or no accumulation of snow or ice pellets (sleet) expected in most areas. (Forecaster should include appropriate local warning/advisory information)

FREEZING RAIN (Subtype 5): Significant accumulations of freezing rain expected. (Forecaster should include appropriate local warning/advisory information)

MIXED LIQUID WITH FREEZING RAIN (Subtype 6): Rain possibly mixed with snow/sleet or freezing rain (include appropriate types based on synoptic/mesoscale situation). {Low lying areas and overpasses may experience significant icing, include if appropriate to the situation}

MIXED LIQUID (Subtype 7): Rain possibly mixed with snow or sleet but no snow or sleet is expected to accumulate. (include appropriate types based on synoptic/mesoscale situation). {Higher elevations or western areas or overpasses may experience accumulations of snow or sleet, include if appropriate to the situation}

ALL RAIN (Subtype 8): Rain.

7.2 APPENDIX 2: Case Counts

STATION/REGION	FROZEN CASES	FREEZING CASES	LIQUID CASES
AHN	11	8	118
BNA	21	3	68
CHS	3	2	39
GSO	30	33	159
HAT	4	0	55
HTS	218	8	344
IAD	86	14	280
WAL	14	2	30
COAST	7	2	94
PIEDMONT	41	41	277

Table 7.1 Case Counts used in TOP DOG Analyses. Frozen/Freezing/Liquid cases as defined in Table 2.4.